



Sensor technology foresight

Andersen, Per Dannemand; Jørgensen, Birte Holst; Rasmussen, Birgitte

Publication date:
2001

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Andersen, P. D., Jørgensen, B. H., & Rasmussen, B. (2001). *Sensor technology foresight*. Risø National Laboratory. Denmark. Forskningscenter Risoe. Risoe-R No. 1292(EN)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Sensor Technology Foresight

Per Dannemand Andersen

Birte Holst Jørgensen

Birgitte Rasmussen

Sensor Technology Foresight

Per Dannemand Andersen

Birte Holst Jørgensen

Birgitte Rasmussen

Abstract. The Sensor Technology Center A/S (STC) in co-operation with Risoe National Laboratory has carried out a sensor technology foresight in order to strengthen a strategic outlook on sensor technology. The technology foresight (with a timeframe of 2000 to 2015) has been performed in the period October 2000 – September 2001.

The conclusions of the sensor technology report are based on 1) a scanning of existing forward looking literature on sensor technology, 2) a number of workshops with Danish and international participants and 3) an international survey with 174 respondents. Half of the respondents came from universities and other research institutes, and approximately one-third came from industry.

The study has analysed **six types of sensors** (covering 13 sub-types) and, in addition, a number of systemic issues. All three sources of information indicate the same pattern regarding future attractiveness of sensor types. MEMS- and optical sensors, biochemical/biological sensors together with systemic issues are all expected to be the most interesting sensor types over the next 10 years regarding market volume. General **technological key features** are expected to be quite generic: low price, small size, robustness, dispensability, and the ability to be self-calibrating. Future sensors are expected to be integrated systems with multiple applications.

The **market sectors** most influenced by new sensor technology change from topic to topic. But a general conclusion is that health care is the market sector most heavily impacted by new sensor technology. It also appears that new sensor technology will affect food processing and the environment sector. Some impact is made on sectors such as agriculture, chemical engineering, domestic and other appliances, security and defence, transport, and energy. Less impact is made in sectors such as construction/housing, wood/textile, IT/communication, and metal and plastic processing. The survey does not challenge the generally accepted perception that the transport sector also in a 10 year future will be a driving force in developing new sensor technology.

ISBN 87-550-2938-8; ISBN 87-550-2939-6 (Internet)
ISSN 0106-2840

Print: Pitney Bowes Management Services Denmark A/S, 2001

Contents

1 Introduction 5

2 Summary 7

3 Topics in Sensor Foresight 10

3.1 Introduction 10

3.2 Definitions 10

3.3 Technology Mapping 11

3.4 Technology scanning - needs and possibilities 19

3.5 Statements about future sensor technology 23

3.6 Summary of outcome of the technology mapping and scanning 28

4 Survey 30

4.1 Introduction 30

4.2 General remarks 30

4.3 The ranking of topics 33

4.4 Technology and market 40

4.5 Period of occurrence 44

4.6 Market sectors most heavily impacted 45

4.7 Constraints/barriers for realising the statement 47

4.8 Summary of survey results 48

5 Conclusion 51

6 Literature 55

Appendix A: Questionnaire

Appendix B: Case studies

Appendix C: Technology scanning

Appendix D: 122 statements

Appendix E: Results of survey (Delphi)

Appendix F: Ranking of 46 statements

1 Introduction

Sensor technology is one of the technologies that will play a major role in the future. It can be used in all sectors of industry and can give a product the added value that makes it competitive. In a knowledge-based economy only firms that are very innovative, grow fast, and create most value will do best in tomorrow's competition. Sensor technology is a rapidly growing area of research with many products already on the market, which promise to continue to have a critical role in technologies of the future. Sensors span all sectors of industry and often offer products the innovative edge that lead to their competitive advantage. Knowledge about sensors, their applications and their future developments thereby helps to position organisations to grasp emergent opportunities.

Sensor Technology Center A/S (STC) is the result of a joint initiative by five Danish Authorised Technological Service Institutes (the so-called GTS-institutes) comprised of Biotechnological Institute, Danish Technological Institute, FORCE Institute, DELTA Danish Electronics, Light & Acoustics, and DHI - Water & Environment. STC is part of the Danish Sensor Initiative to which the Danish government has granted app. 14 million EUR for a special effort on sensor technology.

STC aims at facilitating the knowledge and competencies necessary for the development, production, and application of sensors. STC establishes and operates projects necessary for the development of new sensor technologies. One of the foremost tasks of STC is also to create networks.

The Technology Scenarios group at Risø National Laboratory has assisted STC in carrying a technology foresight study in order to strengthen a strategic outlook on sensor technology.

The sensor foresight project has four objectives.

1. To present some scenarios of the future developments in sensor technology with respect to technology, application and market issues in a time-frame of 2000 to 2015.
2. To contribute as decision support in prioritising research, development and commercialisation of sensor technology.
3. To maintain and develop STC's networks within sensor technology.
4. To test elements of a Technology Foresight methodology in a narrow area of technology.

The target groups for the results of the investigation are for example manufacturers and users of sensors, the R&D community, public authorities, and the STC as a consultancy centre in the sector industry.

The project has included six main tasks, which are presented in the figure below.

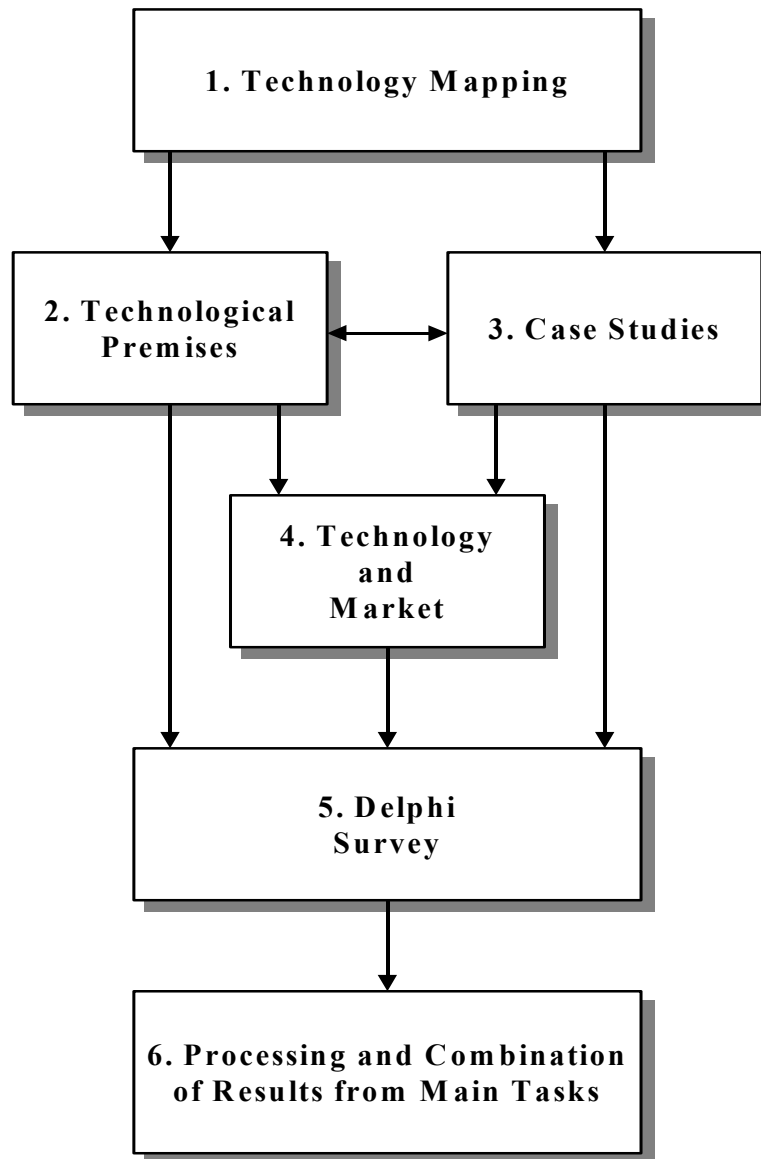


Figure 1.1. Overview of project tasks

1. Technology mapping: Desk research to identify the boundaries and categories of the technological landscape to be analysed.
2. Technology Premises: Expert panel to establish the state-of-the-art within sensor technology and to define boundary conditions for sensor technology over the next 15 years.
3. Case studies: To analyse important mechanisms in sensor technology breakthroughs.
4. Technology and Market: Expert panel to establish a prospective discussion of the development trends of the interaction between market and technology over the next 15 years.
5. Survey: Performing a survey in order to improve validity and reliability of the sensor foresight.
6. Conclusion: Discussion and processing of the various elements of the previous tasks within technology mapping and scanning, case studies, expert panels and the survey.

The foresight project has been performed in the period October 2000 – September 2001.

This report presents the findings of the project. In Chapter 2 a summary of the report is presented together with the main conclusions. Chapter 3 focuses on the technology mapping and scanning, primarily conducted in the first four phases of the project. Hereafter, the findings from the survey is presented in Chapter 4. Eventually, the conclusions from the overall project are presented in Chapter 5. More detailed information from the technology foresight is presented in the appendices.

2 Summary

Sensor technology is a rapidly growing area of research with many products already on the market, which promise to continue to have a critical role in technologies of the future. Sensors span all sectors of industry and often offer products the innovative edge that leads to their competitive advantage.

Therefore, the Sensor Technology Center A/S (STC) in co-operation with Risø National Laboratory has carried out a sensor technology foresight in order to strengthen a strategic outlook on sensor technology. The technology foresight (with a timeframe of 2000 to 2015) has been performed in the period October 2000 – September 2001.

Sensors and sensor systems perform a diversity of sensing functions allowing the acquisition, capture, communication, processing, and distribution of information about the states of physical systems. This may be chemical composition, texture and morphology, large-scale structure, positions and also dynamics. It is a characteristic feature of a sensor that the device is tailored to the environment in which it is to operate.

The conclusions of the sensor technology report are based on 1) a scanning of existing forward looking literature on sensor technology, 2) a number of workshops with Danish and international participants and 3) an international survey with 174 respondents. Half of the respondents came from universities and other research institutes, and approximately one-third came from industry.

The study has analysed six **types of sensors** (covering 13 sub-types) and, in addition, a number of systemic issues. All three sources of information indicate the same pattern regarding future attractiveness of sensor types. MEMS- and optical sensors, biochemical/biological sensors together with systemic issues are all expected to be the most interesting sensor types over the next 10 years regarding market volume. Expectations of present and future market importance of a number of sensor types are indicated in Figure 2.1.

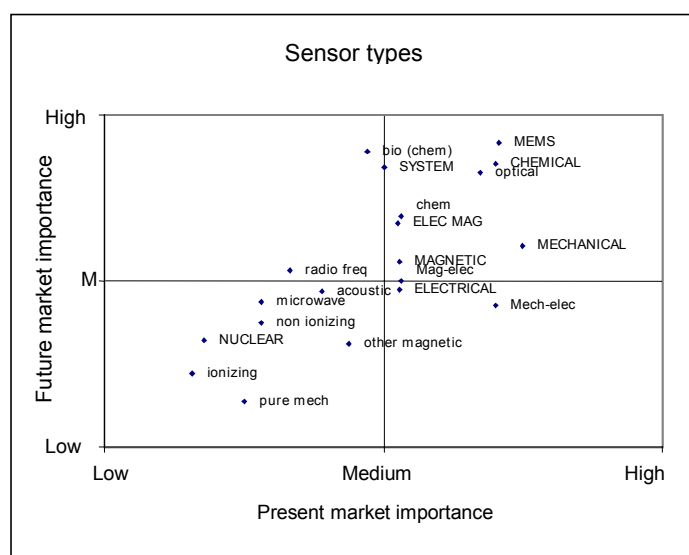


Figure 2.1: Estimation of present and future market importance for sensors

The study indicates some **technological challenges**. The expected market impact for ultra-small biosensors and the use of polymers and miniaturised energy supply for integration in self-contained sensors is much larger than the technological feasibility.

Areas in which the technological feasibility is larger than the potential market volume include fibre optics sensors, radio frequency sensing, eddy-current and ultrasound for on-line sensing in production systems, nuclear based sensors and the use of chemometrics.

Ambiguous expectations have been found regarding biosensors. On the one hand widespread use of biosensors is included in the top ten list (primarily due to high potential market volume). On the other hand the inclusion of implanted bio-sensors, sensors substituting human sensing and specific sensors using living organisms are ranked low (primarily due to low technological feasibility).

General **technological key features** are expected to be quite generic: low price, small size, robustness, dispensability, and the ability to be self-calibrating. Future sensors are expected to be integrated systems with multiple applications.

The **market sectors** most influenced by new sensor technology change from topic to topic. But a general conclusion is that health care is the market sector most heavily impacted by new sensor technology. It also appears that new sensor technology will affect food processing and the environment sector. Some impact is made on sectors such as agriculture, chemical engineering, domestic and other appliances, security and defence, transport, and energy. Less impact is made in sectors such as construction/housing, wood/textile, IT/communication, and metal and plastic processing. The survey does not challenge the generally accepted perception that the transport sector also in a 10 year future will be a driving force in developing new sensor technology. See Figure 2.2.

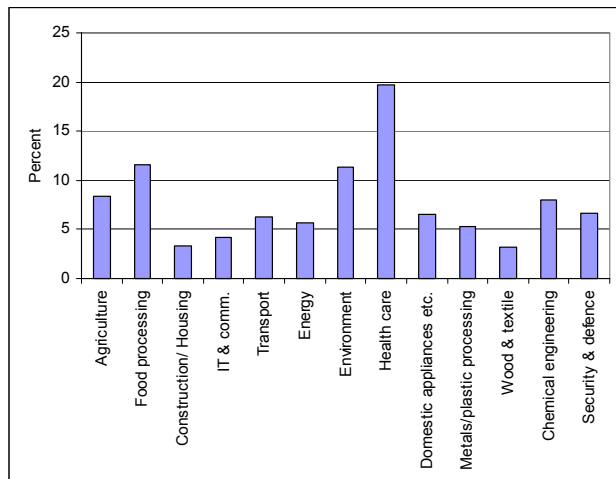


Figure 2.2: Market impact for all sensor types

Barriers for realising the new sensor technologies cover a number of framework conditions that are central to the development of the technology and the markets. These are first and foremost limited cross-disciplinary collaboration. But lack of qualified human resources and lack of cross-sectorial collaboration are also estimated as important barriers. The lack of standardisation is mentioned, in particular regarding the topics on sensor communications systems and artificial noses. Lack of public acceptance is the case for topics such as implanted sensors and X-ray sources for industrial processes. See Figure 2.3.

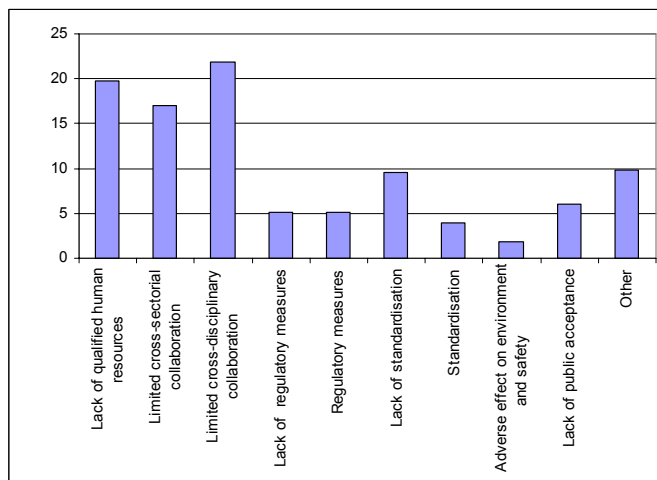


Figure 2.3: Barriers for realising the sensor topics

3 Topics in Sensor Foresight

3.1 Introduction

Technology foresight depends on technology insight. One way of embarking on a technology foresight is to define the system under examination. This initial step is called technology mapping. It is a categorisation and classification of the technological landscape in order to make an overview of the object of analysis and to identify the boundaries. Technology mapping is followed by and frames the structure of the next step of the technology foresight process - technology scanning.

Strategic technology scanning is concerned with “looking ahead”. It is essentially an exploration of the future technological landscape, aiming at discerning its major features and significant patterns of change.

A central part of the sensor technology foresight is to identify and select essential topics related to sensor developments. These topics are reframed as statements to be assessed and evaluated by experts, first by smaller expert panels and subsequently validated by a large group of sensor experts through a survey.

The technology mapping and scanning thus comprises the following steps:

- Definition of sensor technology (section 3.2)
- Technology mapping (section 3.3)
- Technology scanning (section 3.4)
- Formulation and selection of statements (section 3.5)

3.2 Definitions

Sensors can be defined in several ways. According to McGee et al. (1999) sensors can be defined as “systems” that refine and extend the human facilities of “sensing” and “perception” In other words, sensors are human-made elements embedded within human-machine systems which help humans to acquire information, by the process of sensing, and to handle data, by performing information handling operations.

Furthermore, Kretschmer & Kohlhoff (1997) characterise a sensor is a signal-processing system with two features:

- A primary feature aiming at measuring physical, chemical or biological units/dimensions following according to a specified principle
- A secondary feature of signal translation, which through one or several steps appears as exit signal.

In this study, we have chosen to use the following definition:

- Sensors and sensor systems perform a diversity of sensing functions allowing the acquisition, capture, communication processing, and distribution of information about the states of the physical systems. This may be chemical composition, texture and morphology, large-scale structure, position, and also dynamics. It is a characteristic feature of that the device is tailored to the environment in which it is to operate.

This definition gives a preliminary delimitation of sensor technology. It is further explored in the technology mapping.

3.3 Technology Mapping

Technology mapping within the sensor technology field is a categorisation and classification of the sensor technology domain without losing the holistic perspective. The purposes are:

- to determine definitions and preliminary delimitation of sensor technology and the sensor technology domain ensuring that all relevant aspects and topics are recognised
- to provide a familiarity of the terminology used within the sensor field and an agreement on language/concept, which is important for the subsequent discussions between the different researchers, stakeholders, and experts
- to structure the subsequent technology scanning (e.g. organisation and structure of data, information, workshops, and questionnaires) with the overall goal to seek major distinguishing features and drivers of change in the sensor technology domain
- to identify a gross list of sensor experts to be consulted in the technology foresight process (e.g. workshop participants, questionnaire respondents, case study interviews).

Many different methods, theories and tools are used in sensor developments and further sensor technologies have a huge variety of application areas. Preparing a technological mapping of sensors can for this reason be carried out from several different starting points and on different dimensions. We have chosen to structure the collection of data and information for the synthesis of possible future developments of sensor technologies by the following three dimensions:

Dimension 1: Sensor physics and sensor systems - focus on technologies

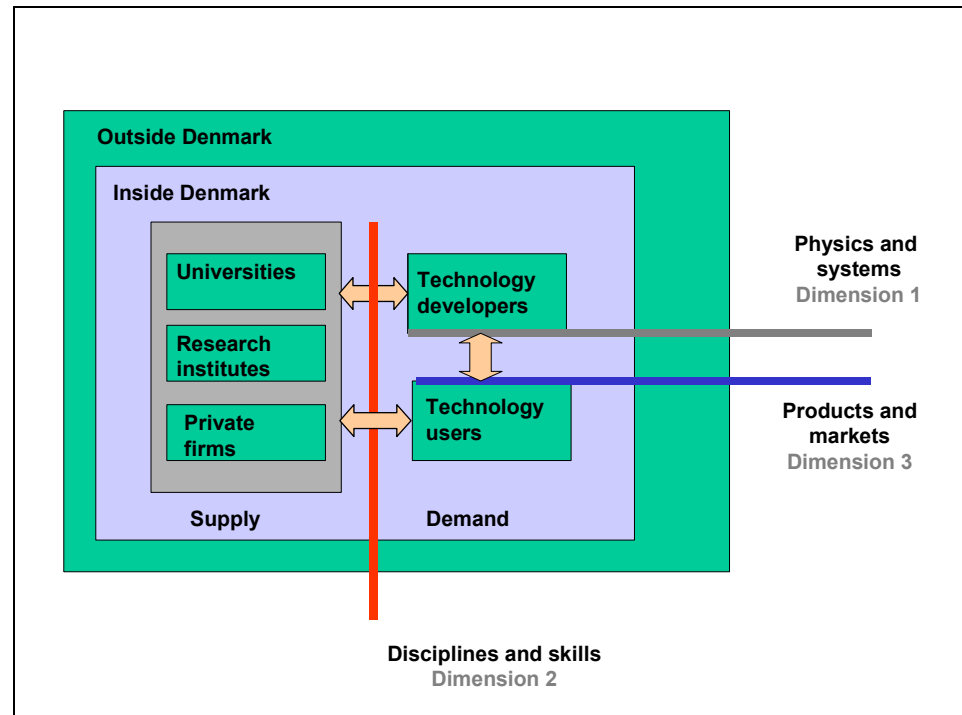
Dimension 2: Generation and transfer of expertise and skills - focus on disciplines and skills

Dimension 3: Technology users and areas of application - focus on products and markets

These three dimensions are chosen because they can in three different ways provide an indication and understanding of the flow and availability of knowledge and know-how - both parameters considered to be of high importance in future sensor developments. A knowledge-based technology mapping model has been proposed because knowledge, capabilities, and competencies are some of the most important drivers of change (i.e. carriers or barriers) in technology development.

In Figure 3.1, the three dimensions are depicted in a diagram comprising actor archetypes and knowledge interfaces in the field of sensor technology and the relations between them. The main purpose of the diagram is to illustrate the generation and transfer of different types of knowledge and know-how to ensure

that all aspects are covered in the analysis more than to prepare a truthful picture of the actors of the sensor technology world.



Source: RAND Europe, 1998.

Figure 3.1: Mapping of knowledge and know-how flows – three dimensions

On the *demand side* we have firms with a need for sensor technologies. These firms are divided into two categories:

- Technology developers are organisations that produce or develop sensors. The economic success of these organisations depends on bringing the sensor to the market and on their competitive advantage compared to other sensor developers.
- Technology users consist of organisations that to some extent use sensors in their product or production process. Their product or services are thus not only sensors, but products, services e.g. using sensors. The technology users have a thorough understanding of and are close to the technical measurement problem.

On the *supply side* we have the entire knowledge infrastructure, which comprises the following institutions/elements:

- Higher education comprising higher education and basic research
- Research institutes comprising, for example technological service institutes, national laboratories, research centres
- Private research organisations
- Research abroad (With and without links to Danish research)

In order to identify possible drivers or problems of the technology system, special attention is put on the links and relations between the different actors of the technology system, i.e. between technology producers and technology users and between demand and supply side.

Sensor types and systems (Dimension 1)

The classification of sensors is based on classical taxonomy as the enabling key in bringing order to the study of sensor systems. McGhee et al (1999) propose a sensor type classification, where sensors are grouped according to the COMETMAN energy classification:

Chemical sensors, including gas, immunological, pharmaceutical, and food industry units

Optical sensors

Mechanical sensors, such as in manufacturing, robotics, medicine, mechatronics

Electrical sensors

Thermal sensors

Magnetic sensors

Acoustic sensors

Nuclear sensors

This classification of sensors was presented to a group of sensor experts as part of the technology foresight (Workshop 31.10.2000). Based on the COMETMAN classification, the experts agreed on a classification based on sensor physics and systemic issues, see Table 3.1.

Table 3.1 Classification of sensor technology

	Classification	Examples
Sensor physics	1A Electromagnetic	Gamma radiation. Optics. Microwave. Radiowaves. Eddy current,
	1B Mechanical	Sound (infra- to ultra-). MEMS. Fluid.
	1C Electrical	Electrostatic.
	1D Magnetic	
	1E Chemical	Affinity (molecular recognition). Catalytic reactions. Electrochemistry. Biochemistry.
	1F Nuclear	Nuclear Magnetic Resonance.
	2 Combination of 1A - 1F	Opto-acoustics. Membrane technology.
System	3 Systemic issues	Materials technology. Fluid physics. Information processing (signal and data). Packaging. Production technology (production of sensors). Interfaces (e.g. between sensors and object). Integration Value chain.

This classification was used as the guiding principles for technology mapping and scanning throughout the sensor technology foresight, including the framing and organisation of statements about the future developments within sensors and sensor systems.

Generation and transfer of experience and skills (Dimension 2)

Sensor technology is an interdisciplinary science comprising expertise and skills from various scientific disciplines. This makes a disciplinary-based approach difficult.

Referring to Figure 3.1, the distinction and relationships between the different actors are not well defined, and consequently neither are the experiences and skills related to actors. Many actors often feel a relationship to more than one actor category, e.g. a technology service institute can act as a sensor developer as well as a sensor user.

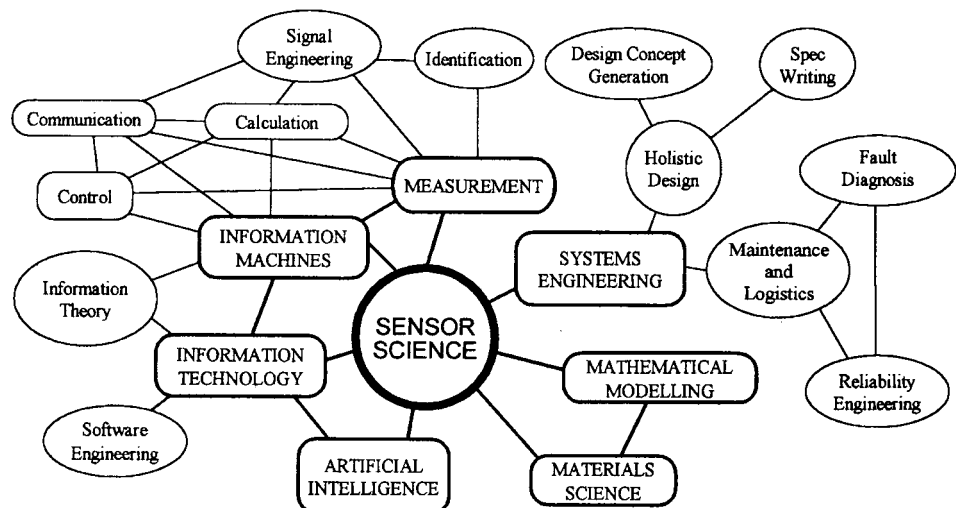
The generation and transfer of experiences and skills is therefore described using multiple perspectives:

- A disciplinary approach
- A value chain
- Two illustrative case studies on the development and use of sensors

Disciplines – sensor science and sensor development

The disciplines and competencies in sensor technology can be described and structured in several ways. Figure 3.2 and Figure 3.3 presents two different approaches as how to visualise some of the sensor science disciplines and competencies.

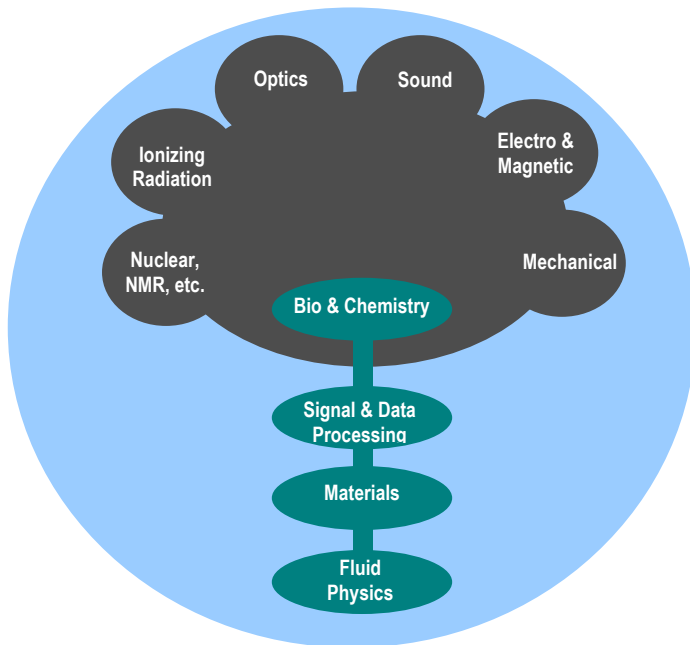
Figure 3.2 illustrates the systemic nature of sensors where an essential and fundamental contributory discipline to an organised science of sensing is the field of systems engineering with its implicit constituent, which encourages a holistic approach to the question of sensing and transduction. Further, sensors are important elements belonging to the class of information machines which is made up of machines for measurement, calculation, communication and control. Consequently, the underlying theory of information handling is also important. (Mc.Ghee et al., 1990).



Source: Mc.Ghee et al., 1990.

Figure 3.2. Bubble and block diagram showing the contributory disciplines of sensor science

Figure 3.3 contains a more simple approach focusing the basic disciplines and the necessity of establishing groups of scientist covering the necessary disciplines and experiences. The disciplines that form the basis for sensor development are signal and data processing and materials. Fluid physics are underlying disciplines, whereas the rest falls under “sensory physics” (the dark area).



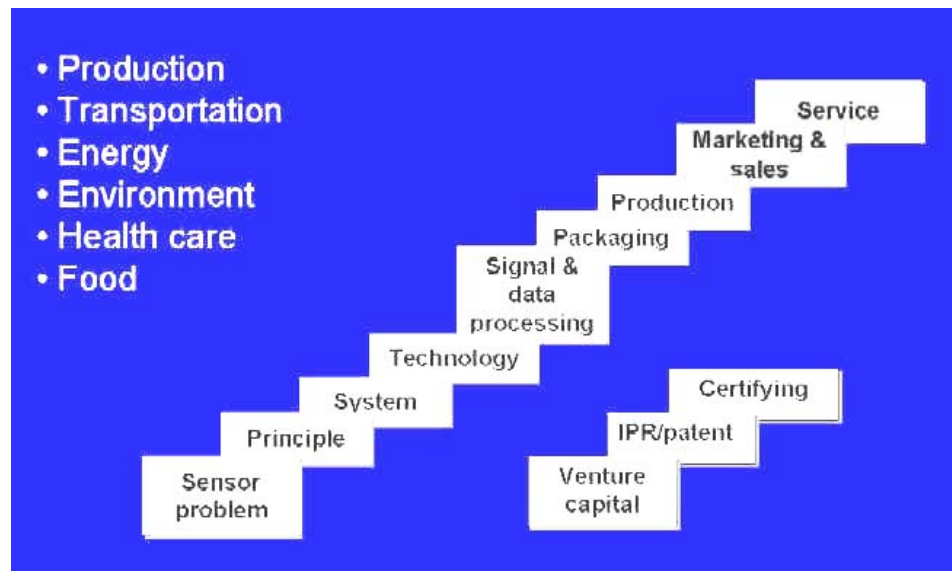
Source: STC, 1999.

Figure 3.3 Sensor knowledge and competencies

Value chain

The realisation of a sensor product requires a number of tasks to be completed ranging from product definition over system configuration, implementation, certification, marketing and service. Few institutes or firms possess all the competencies necessary for the realisation of a product, and as in other contexts this can be viewed as a value chain.

A value chain is an interdependent system or network of activities, which all contribute or add to buyer value (Porter, 1990). The value chain provides a tool for understanding sources of competencies and costs and it exposes the sources of differentiation. Regarding sensor technologies, the underlying assumption is that a considerable knowledge base exists, whereas the total value chain is often either difficult to establish or lacking important links (STC, 1999).



Source: STC, 1999.

Figure 3.4. Value chain of sensors

Two case studies on the development and use of sensors

As a multi-disciplinary area sensor technology makes it imperative that firms, research institutes, and universities co-operate on the development and commercialisation of sensors.

Two case studies illustrate the creation and diffusion of knowledge in public-private direct interaction within sensor technologies. They are what we consider to be exemplary in terms of the ability to develop new knowledge, the ability to communicate this knowledge and the ability to use this knowledge in industry. Among scientists, considerable debate has focused on whether knowledge is technology-driven or market-driven. We tend to overcome this dichotomy by presenting two extreme cases:

- A market-pull case – the development of a computer input device (Box 3.1)
- A technology-push case – the development of a silicon microphone (Box 3.2)

For extended case descriptions, see appendix B.

Box 3.1. Market pull – computer input device

The demand

The computer device, the Free Pen, was driven by the idea that devices could and should be adapted to the body (and not the other way round) in order to avoid ergonomically health problems. The entrepreneur found sufficient financial funds to explore the realisation of the idea and started searching for the appropriate technology.

The search for a technology

The search brought him to a national research laboratory and a senior scientist working on optical lasers and speckles for measuring the rotation of ship propeller shafts. The technology was patented, but was not applied in a commercial product. Hence the opportunity arose to apply it on a miniaturised scale. The collaboration included the necessary adjustments of the technology, assistance to additional patent applications, assistance to identify subsidiaries and to specify a production contract with an international firm.

Market introduction

Due to financial constraints, the product was introduced too early on the market without having solved all technical problems. The firm had to suspend its payment and reorganise its activities with additional venture funding. The second generation cordless, programmable and web-optimised computer pen, the Zeptor, was developed and introduced on a market no longer restricted to the narrow, ergonomic-demanding welfare markets, but also including new life style customer segments on the global PC market.

The *knowledge interaction* between the firm and the national research laboratory was an extraordinary match between product and technology, which led to three firm patents, the commercial development of a new technology and the introduction of a new product in the global markets. The interaction was facilitated by a well functioning co-operation characterised by trust, enthusiasm, and openness due to clear patent regulation, a reliable contract and a successful out-sourcing strategy. The interaction was hampered by the difficult financial situation in the critical stages of the project.

Box 3.2. Technology push – a silicon microphone

Background

The development of a silicon microphone for hearing instruments is the story about a technology searching for real life problems/applications and a private firm searching for a way to gear its R&D activities.

A research and development centre for advanced micro-technology in semiconductor materials wanted to push the technology into new applications and thereby gain new knowledge. It presented a Ph.D. project to a local component supplier to the hearing aid industry as a favourable means for exploring alternative technologies for conventional miniature microphones. Although the silicon microphone technology was known in academia for more than 20 years, one single Ph.D. project would not fulfil the ambition to develop a silicon microphone for hearing instruments.

A further development was made within a Centre Contract, which was a recently introduced governmental support scheme for strategic R&D collaborations, in particular the involvement of Authorised Technological Service Institutes as an institutional bridge between research and industry. This model would allow for the exclusive problem solving regarding the silicon microphone, but founded on divergent interests and goals.

The application of the technology

From the beginning, a certain division of work was developed, guided by the constant concern of the firm to apply the technology in a commercial product. But the development was much more complicated and time consuming than foreseen, especially with regard to the production of the wafer. Therefore an additional research project on “High-Performance Interconnect and Stacking” (HISTACK) was made.

Knowledge interaction

At the end of the Centre Contract period, a demonstration model of the world’s smallest silicon microphone was developed. There was still a long way to go to finalise a prototype, not to mention to start up the production of a silicon microphone. The cost price in small quantities was still not competitive with the traditional microphone. This induced the firm to look for other applications than the hearing instruments, e.g. within telecommunications. Two product-specific patents were approved (membrane and stacking) and together with the Authorised Technological Service Institute, a patent was approved within packaging.

For the Authorised Technological Service Institute the joint project was a kick-start of its competence building within silicon technology. Yet, for the research centre the project meant new research results, a patent application, and most importantly, the education of a number of M.Sc.s and Ph.D.s working with the development and application of the technology.

Important for the knowledge interaction were the governmental centre contract and public research programmes, the time consuming but necessary contract negotiation, the cautious building of the research team, and the development of a critical mass within silicon technology.

Technology users and areas of application (Dimension 3)

This dimension focuses on the practical use of sensors and user requirements. It comprises, e.g.:

- measurement object and sensor working environment
- requirements to sensitivity and precision
- requirements to reliability and robustness
- economy (price of sensor systems)
- standardisation of sensor systems

One way to classify technology users is the business cluster approach, which focuses on the supplier and business relations among firms.

Not all business clusters are important to the use and application of sensors. On basis of expert judgements during the technology foresight study the following market sectors are found to be central to sensor development:

- agriculture
- food processing
- construction / housing
- IT / communication
- transport
- energy
- environment
- health care
- domestic and other appliances
- metal / plastic processing
- wood / textile
- chemical engineering
- security / defence

These business clusters or markets are used when assessing the future market possibilities and opportunities for sensor technology in the subsequent technology scanning and development of statements on the future development of sensors.

3.4 Technology scanning - needs and possibilities

The step following the technology mapping is the scanning process. Strategic scanning is concerned with “looking ahead”. The central questions are: When we scan, what do we look at? What do we look for? (Wyk, 1999).

Scanning enhances technology foresight by seeking major distinguishing features in the technological landscape. Strategic scanning thus views the technological domain as an observable totality with clearly identifiable parts (Wyk 1999).

The scanning comprises the following levels:

Level 1: The overall trends for the development of a modern welfare state which directly or indirectly are expected to have an impact on the technological development.

Level 2: The identification of topics and issues of sensor technology, based on literature and expert workshops.

Overall trends in society (Level 1)

The Danish Agency for Trade and Industry has recently published a report (Erhvervsfremme Styrelsen, 2000) on trends that are supposed to influence Danish industry in the next 10 years. The identification of these trends is based on international literature and the trends thus reflect some general features in highly developed countries. The trends comprise seven macro-trends and a number of related micro-trends:

Consumption and feelings. The consumer is oriented towards product and services that appeal to their feelings and tell a story appropriate to their lifestyle or political opinion. More production and consumption in and outside the home for example do-it-yourself products, restaurant, catering services, etc.

Health and focus on biotechnology. Ageing population and an increased focus on health creates a market for devices for self-diagnosis and health. Biotechnology will revolutionise the health sector. More effective health care and increased self care.

IT era. IT in more and more products. Internet as future dominating market place. The mobile society.

The global industry. Global investments and ownership. Increased importance to regional trade blocks/areas as, for example, the EU. The Nordic countries as nearby market. Comeback for Eastern Europe.

Knowledge – the most important raw material. Knowledge workers in focus. Innovation through research. Increased flexibility in the labour market.

The knowledge-based organisation. Networks and project organisation. Integrated information networks.

The new boundaries of the nation state. More power to international organisations. Liberalisation and tendering public services. Closer public-private co-operation. National competitiveness based on a favourable business environment/framework.

The trends have been used as input for expert judgements on sensor technologies, both in relation to technological premises and to technology and markets.

Technology scanning - topics and issues (Level 2)

The technology scanning was performed through scanning of the open literature and by arrangement of four thematic expert workshops and resulted in a large number of topics central to the future development and use of sensors.

Workshops

- Workshop I (31 October 2000): Workshop with Danish sensor experts. Theme “Technology mapping and structure of sensor technologies”.
- Workshop II (19 January 2001): Workshop with international sensor experts. Theme “Sensor technology premises”.
- Workshop III (29 March 2001): Workshop with Danish sensor experts. Theme “Technology and market”.
- Workshop IV (5-6 April 2001): Workshop with international sensor experts. Theme “Technology and market”

Open literature - main sources

- Sensorik: Überblick und Trends (D)
- United Kingdom Technology Foresight Programme. Delphi Survey
- Forskningsnätverk för tillämpad sensorutveckling och mätteknik (S)
- The 6h technology forecast survey - Japan Toward the Year 2025
- Technology radar. Global views on strategic technologies (NL)
- Industrielle behov for nye sensorer til fysiske målinger - analyse på baggrund af telefoninterview af 23 virksomheder (DK)
- Sensorteknologi - Danish Agency for Trade and Industry

Table 3.2 summarizes the number of topics found by the different sources. The result of the technological scanning including all topics can be found in appendix C.

Table 3.2. Number of topics identified by the different sources.

	Number of topics
Open literature	62
Workshop I	30
Workshop II	79
Workshop III	15
Workshop IV	31

The outcome of the scanning was a sample of highly diverse and complex topics. They are grouped under four headlines:

- Generic issues which are of relevance for almost all types of sensor systems. Illustrative examples of topics are:
 - *Practical use of ultra-small bio-sensors for use in medical and other applications, based on the utilisation of biochemical reactions. (NISTEP, 1997).*
 - *Widespread use of non-invasive sensing techniques applicable across a wide range of manufacturing industries to replace invasive sensing techniques. (Loveridge et al., 1995).*
- Dominant sensors, i.e. sensor types that are mentioned most often. Illustrative examples of topics are:
 - *Related to the growing importance of electronics in sensors and sensor systems is the development of devices that combine both functions. Here the development of microelectromechanical systems (MEMS) offers great potential. Their progress will depend on bringing together research in materials, fabrication and electronics. (Moore et al., 1997).*
 - *Sense monitoring via implanted biosensors e.g. early cancer warning, major failure warning (Workshop II).*
- Dominant areas of applications i.e. areas of application most often registered during the scanning process. Illustrative examples of topics are:

- *Remote sensing for monitoring, understanding, management and utilisation of natural resources and the environment, e.g. satellite instrumentation, with instruments in aircraft, or by land-based instrumentation (Hollington, 1999).*
- *Point of care medical diagnostics with dispensable micro-chip for biochemical analysis (capillary separation and optical detection). (Workshop II).*
- Barriers and carriers, i.e. drivers of change for future sensor development. Illustrative of topics examples are:
 - *Barriers to the introduction and wide spread use of sensors are the costs and a form compatible to the attached electronics. Important are thus usability, reproducibility, selectivity vis-à-vis measurement dimension and long-term stability (Kretschmer & Kohlhoff, 1997).*
 - *Sensors that work in an industrial environment must meet stringent performance standards. They must be: robust, reliable, maintainable, self checking and automatically self-calibrating where possible, cost effective, able to operate in a changing production environment. (Moore et al., 1997).*

Table 3.3 summaries the issues and topics most commonly referred to during the technology scanning.

Table 3.3 Technology scanning observations

Generic issues	non-invasive, non-contact multiple sensor systems systemic networks hybrid sensors array sensors implanted sensors embedded sensors lab-on-a-chip sensing miniaturisation nano scale integration of sensors, actuators and controllers wireless transmission standards of measurement encapsulation
Dominant sensor types in the technology radar	Biosensors Biometric chemical sensors MEMS optical sensors, lasers
Dominant areas of application	Safety reliability optimisation quality of measurement, product intelligent/smart materials monitoring control intelligent information accuracy sensitivity diagnostic sensing
Carriers and barriers	Price Size Dispensable Robustness self-calibrating

3.5 Statements about future sensor technology

The statements about the future development and application of sensor technologies are developed in a two-step process:

1. **The formulation of statements** regarding the future development and application of sensor technologies
2. **Selection of key statements** for the future development and selection of sensor technologies.

Formulation of statements

The expected future development and application of sensors were formulated by experts as a so-called statement.

The formulation of statements was guided by the following:

“A statement must be a concise expression of the event, achievements or other phenomenon upon which views are sought. In as few words as possible, an unambiguous expression of what the questioner has in mind must be achieved, which incorporates any key conditions, but which excludes separate issues that warrant one or more additional topics” (Loveridge et al., 1995).

In addition, a syntax was developed and experts were asked to formulate statements according to it. The sensor statement syntax contains the following main elements:

Development stage referring to different stages of development

- Elucidation: to scientifically and theoretically identify principles of phenomena
- Development: to attain a specific technological goal or complete a prototype
- Practical use: the first practical use of an innovative product or service
- Widespread use: significant use: significant market penetration to a level where a product or service is in common use

Sensor type referring to dimension 1 of the technological mapping.

Basic technology referring to dimension 2 of the technological mapping.

Application referring to dimension 3 of the technological mapping.

A total of 125-130 statements were formulated, based on literature and the expert workshops. The statements have been classified according to the classification scheme presented in Table 3.1:

- Electromagnetic (optical, microwave, radio frequency)
- Mechanical (purely mechanical, electromechanical, MEMS, acoustics)
- Electrical
- Magnetic (electrical, other magnetic sensors)
- Chemical (chemical, biochemical & biological)
- Nuclear (non-ionising, ionising)
- Systemic issues

The total list of statements can be found in appendix D.

Rating and selection of statements

The validation of expert statements passes through a questionnaire where statements are presented to a larger group of experts. Such a questionnaire must not be too voluminous. The number of statements was therefore limited to about 50 statements to which experts were asked to answer a number of variables. Consequently, the task was to select 50 statements out of the 125-130 statements. This was done in a two-step process:

- 1) Rating of statements and sensor types
- 2) Selection of statements.

Rating of statements

The criteria for ranking statements were market impact and technological uncertainty:

- *Market impact* refers to the market potential of the statement. By this we are looking for those statements which may lead to a significant influence, impact, or change upon a market. This could be in terms of large volume, or high degree of turnover. Or if the statement deals more with a development issue, a high market impact could be the potential to revolutionise an existing market, develop an altogether new market or instigate some kind of fundamental change in market structure, size, or profitability over the long term. A low ranking of a statement would imply business as usual, a negligible effect or no effect on markets at all. We may not expect the realisation of these statements to create many business opportunities.
- *Technological uncertainty* refers to the degree of uncertainty surrounding the potential of the statement. There may be high uncertainty if, for instance, there is not enough information, indeterminate information, or foreseeable but unresolved problems surrounding the technology or its application. Statements with high uncertainty will have some kind of unknowns that affect the feasibility of the technology.

For both dimensions the experts participating in Workshop IV were asked to rate all statements using a scheme as presented below.

Table 3.4. Rating scheme used by experts

	IMPACT		UNCERTAINTY	
	low	high	low	high
SENSOR TYPE				
Statement 1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
.....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
.....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Statement XX	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

The idea was to establish a basis for grouping the statements into four main groups as indicated in

. The statements in the first quadrant (I) are the most essential as they are of high uncertainty and of high impact. These statements are considered the most important by a larger group of sensor experts.

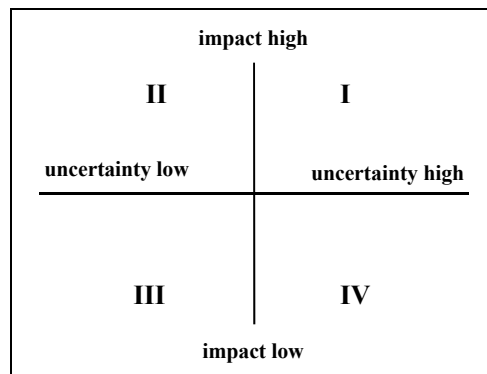


Figure 3.5. Matrix for ranking of statements

The ranking of statements is indicated in Figure 3.6, where each dot in the diagram represents a statement. The diagram was prepared by use of a spread sheet where the average of the experts rating were calculated. Furthermore, standard deviations were estimated to indicate the degree of agreement among the experts. An overall ranking of statements was assessed as the sum of the impact rating and the uncertainty rating. It is remarkable that a large part of the statements are located in quadrant IV with high uncertainty and low impact. The results of the ranking exercise containing all statements and their rating according to impact, uncertainty and impact + uncertainty can be found in appendix D.

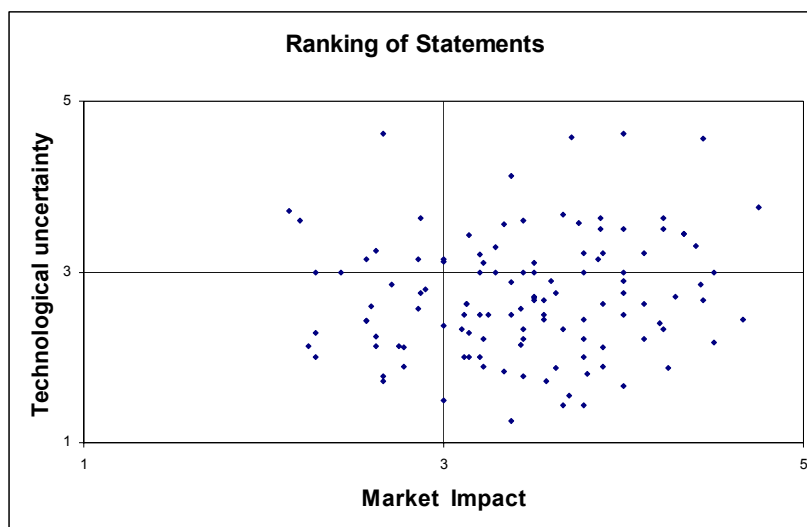


Figure 3.6 Ranking of sensor statements

In Workshop IV the experts had the following remarks to the ranking of statements:

- The ratings reflect what we know and that we may lack vision. The sensors with high rating reflect our ability to make profits and to impact the market. There is an opportunity space within growing areas, but existing areas will also continue
- Several experts expressed that the top-10 list not was surprising.
- The formulation of statements might be unclear with the possibility of different understanding and interpretation of the statement. This could have an influence on the results.

Rating of sensor types

The second questionnaire at Workshop IV focused on the rating of sensor types. The rating parameters were an assessment of the market importance today and the expectations to the future markets, see Table 3.5.

Table 3.5. Rating scheme - sensor types

Sensor types	Your rating of the sensor's present market impor- tance					Your rating of the sen- sor's future market im- portance (app. 15 years)				
	Low		High			Low		High		
Electromagnetic	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
optical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
microwave	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
radio frequency	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Mechanical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
purely mechanical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
electro-	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
MEMS	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
acoustics	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Electrical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Magnetic	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
electrical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
other	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Chemical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
chemical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
biochemical and biological	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Nuclear	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
non-ionised radiation	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ionised radiation	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Systemic issues	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

The ranking according to sensor types is indicated in Figure 3.7. It is of interest to note that sensor types are ranked in two main groups: one in quadrant I indicating an increase in market impact and one in quadrant III indicating a decrease in market impact. Only for the magnetic and the electrical sensors the market impact is assessed to be unaltered.

In Workshop IV the experts had the following remarks to the ranking of sensor types:

- **Optical sensor:** It is expected that optical sensors will replace other sensors, which to some extent explain the increase in market impact. But it is difficult to say whether acoustic or optical sensors will win in the long run. We may see optical replacing acoustic sensors.
- **Chemical and biochemical sensors** might be overrated today but in the future, they will be important. There is a future for combinations of chemical and optical sensors. Now we know about atomic force, DNA analysis, etc.. Nanotechnology will allow carbon nanotubes, tunnel types, quantum dots, hydrogen storage, etc.

- Magnetic sensors are too far to the left, implying that they are underestimated in terms of market importance.
- Mechanical sensors are more important than the results show, especially the electromechanical sensors.
- MEMS should not have been rated so high – it is a buzzword for a technology, simply a tool rather than a sensor type. In the future, however, it will enable many sensor types. Small MEMS sensors are dominated by a surface effect implying the importance of progress in nanotechnology. We spend millions of resources to understand the nanoscale, to understand complications on the first three levels of molecules.
- Electrical: Sensors with electronic elements will replace purely mechanical sensors.
- Nuclear sensors might be rated so low because the group of experts at the workshop do not represent this field. Further, nuclear sensors are an expensive, important technology, yet will never be a high volume product. The only low cost, mass produced nuclear sensors are smoke detectors. There is a strong public resistance towards nuclear technologies.
- Systemic issue: The high rating of systemic sensors is surprising but an explanation could be that systemic issues are an important part of any sensor system. Ceramics will expand in the future, e.g. gas sensors.
- Regarding methodology, filling in the questionnaire one tends to select the middle option (3) in cases of uncertainty or doubt.

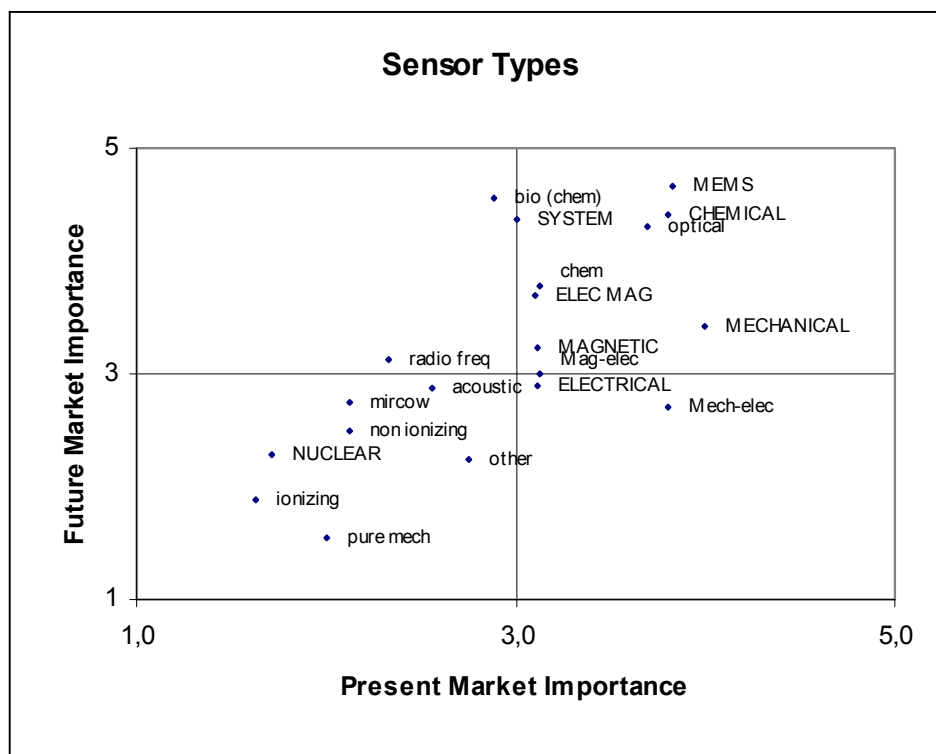


Figure 3.7. Ranking of sensor types

Selection of statements

The following criteria were used for selection of statements:

1. An overall distribution of statements among the sensor categories was decided:
 - electromagnetic (10)
 - mechanical (7)
 - electrical (3)
 - magnetic (5)
 - chemical (15)
 - nuclear (3)
 - systemic issues (7).
2. The rating results from workshop IV.
3. The importance for Danish sensor developers

This has resulted in a questionnaire with 50 statements, which eventually were constrained to 46 due to some overlap in content of some statements (see Appendix A). Table 3.6 contains an overview of the structure of the questionnaire, in which all statements are categorised according to development stage (see the beginning of this section). A few statements are not formulated with respect to development stage. This explains the difference between the total number of topics and the sum of the four categories. As it clearly appears, the categories “Practical use” and “Widespread use” are most often used. It indicates the interdisciplinary character of sensor technology and the dynamic and rapid development of the field. As a consequence, it may therefore be difficult to identify and describe the preliminary stages of development.

Table 3.6. Structure of questionnaire

Sensor type	Number of topics	Elucidation	Development	Practical use	Widespread use
Electromagnetic	11			6	3
Mechanical	7			2	3
Electrical	2			2	
Magnetic	3			3	
Chemical	13	2	2	3	6
Nuclear	2			1	
Systemic issues	8		2	3	2
Total	46	2	4	20	14

3.6 Summary of outcome of the technology mapping and scanning

The first step of the technology mapping and scanning gives us a definition of sensors, which emphasises its systemic nature and the facilities of “sensing” and “perception”.

The technology mapping is conducted using three dimensions, which in different ways provide information on the flow and application of knowledge and

know-how in the development and application of sensor technology. These dimensions are:

- Dimension 1 covers sensor physics and sensor systems. Based on the COMETMAN energy classification, a classification is developed based on sensor physics and systemic issues.
- Dimension 2 refers to the generation and transfer of experiences and skills. It comprises three perspectives of knowledge creation and transfer. Firstly, the contributing disciplines of sensor technology, in which systems engineering is an essential discipline. Secondly, the value chain gives insight into the distribution of competencies from product definition to the final marketing and service, which all contribute to sensor technology. Thirdly, two cases illustrate the dynamic and complex creation of knowledge between firms and research and technological institutes.
- Dimension 3 focuses on products and markets. It outlines a number of business clusters important to the practical use of sensors and user requirements.

The technology scanning takes its departure in the findings from the mapping and is concerned with looking ahead. Firstly, some overall trends are presented which directly or indirectly are expected to have an impact on the technological development over the next ten years. Secondly, a large number of topics are identified in open literature and in four expert workshops on sensor technologies. These topics are grouped in four areas covering: generic issues regarding sensors, dominant sensor types, dominant areas of application, and important barriers and carriers to sensor development.

The scanning includes the formulation and selection of statements regarding the future development and application of sensor technology. A total of 125-130 statements are rated by experts according to expected market impact and technological uncertainty. The final list of 46 statements is selected with due respect to the expert rating, a distribution among different sensor types and Danish sensor development competence.

4 Survey

4.1 Introduction

In this chapter the results from the survey are presented.

It starts with some general remarks on how and when the survey was conducted, and who responded to the survey (section 4.2).

The top ten topics, which are selected based on the combined index of technological feasibility and potential market volume, are presented and described (section 4.3). The description covers the technological feasibility and potential market impact as well as the combined index. Likewise, an overview is made regarding the impact on markets and which barriers are perceived to influence the realisation of the topics. Furthermore, a short description is made regarding the remaining topics, which are ranked in a higher middle list, a lower middle list and a bottom list.

Section 4.4 describes in detail separately and combined the technological feasibility and the potential market volume. The description covers both the top and the bottom topics mostly defined by the technological feasibility, respectively, the potential market volume. In section 4.5, the time occurrence is presented for all and for single sensor types. Markets most heavily influenced by the topics are described in section 4.6. This section is followed by a description of the barriers/constraints for realising the topics (section 4.7).

Eventually, the findings are summarised in section 4.8.

4.2 General remarks

The sensor technology foresight is basically designed as an adapted Delphi investigation. It is designed by two rounds of expert workshops and dialogue about future trends and issues and followed by a larger anonymous survey among experts in order to validate the statements on the future development of sensor technologies.

The survey was conducted as a one round exercise in the period 3 July – 15 August 2001. A reminder was sent out late July.

The total population of the survey was 1,194 experts, of whom 500 were included in the contact database of the STC, 500 were identified in sensor conferences (e.g. “Tranducers ’99” in Japan, “Eurosensors 2000” and “EUREKA Partnering Event – Sensor Technology in European Industry” in Denmark, and “Sensor 2001 – 10th International Trade Fair and Conference” in Germany), 100 experts were nominated by other sensor experts in e.g. the sensor workshops, and the remaining 100 were identified on the Internet. All respondents received an e-mail invitation to participate in the survey. The e-mail invitation gave two options for participating in the survey:

1. Web-based questionnaire (Inquisite) situated on the Risø server
2. Word-based questionnaire attached to the email.

130 out of the 1,194 were returned due to unknown or unidentified addresses or named persons. A total number of 174 filled out the questionnaire, of which 31 were sent as print-outs by mail to STC. The remaining 143 responses were submitted directly via the Internet. Seven of these have been disregarded due to unfilled boxes. This makes a response rate of 16%. Compared to other international technology foresight surveys, the response rate is less than in the British Delphi in 1995 with app. 31% response rate, but more than the German firm Delphi made by Janssen-Cilag making a response rate of 10%.

The following outlines the profile of the responding population, as captured by background information:

- Respondents come primarily from the area of research and development (75%). Some come from general management (8%) and from manufacturing (6%). The remaining respondents come from marketing and other areas of occupation.
- Half of the respondents come from universities or other research institutes (50%). More than one third come from industry (37%). The remaining come from consultancy (8%) and other types of occupation.
- 90% of respondents come from Europe, 5% from the USA and the rest from other continents. The largest group comes from Denmark (38%), but well represented are also Germany (14%), other Scandinavian countries (11%), and the Netherlands (8%).

Respondents cover expertise across all sensor types, though their level of expertise alters slightly as indicated in the figure below. The level of expertise within nuclear sensors, however, seems relatively low.

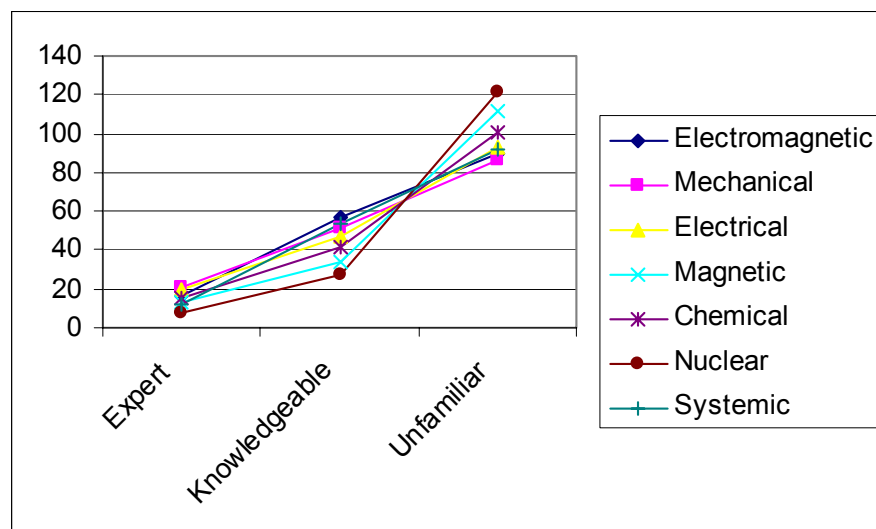


Figure 4.1. Level of expertise across sensor types

The top-five list of statements to which respondents consider themselves as experts:

- No. 14: Practical use of MEMS for miniaturised and low-cost sensor and actuator systems, which can operate as hybrids (N=42).
- No. 41: Practical use of sensors for in-situ calibration or self-calibrating sensors and instruments (N=32).

- No. 12: Widespread use of silicon MEMS sensors in applications with unit prices <5 EUR in food and health care (N=31).
- No. 3: Practical use of fibre optical sensors based on advances in fibre optical technologies (N=30).
- No. 31: Widespread use of biosensors (N=30).

It should be noticed that the statements cover a variety of sensor types, and that they all are supposed to be in stage of practical or widespread use.

The bottom six list of statements to which respondents consider themselves as unfamiliar:

- No. 33: Elucidation of genetic monitoring via implanted sensors to predict a range of parameters, e.g. behaviour, life expectancy (N=125).
- No. 22: Practical use of superconductors in magnetic sensing (N=123).
- No. 37: Practical use of novel concepts of low-cost X-ray sources utilising ionising radiation for industrial process control (N=122).
- No. 46: Practical use of sensors to substitute human sensation, capable of directly stimulating nerves (N=122).
- No. 35: Practical use of specific sensors using living organisms (e.g. genetic modified bacteria) as sensing element (N=121).
- No. 36: Development of DNA-sensors measuring genetic diseases and/or genetically modified food (N=121).

It is remarkable that these statements mainly concern chemical sensors (No. 33, 35, 36 and 37), some of which are characterised as being in the stage of practical use.

As this is a Danish study a relevant question is: does Danish expertise differ from foreign expertise?. In Figure 4.2, we have compared Danish and foreign respondents declaring themselves "unfamiliar" with each statement. No significant differences can be found.

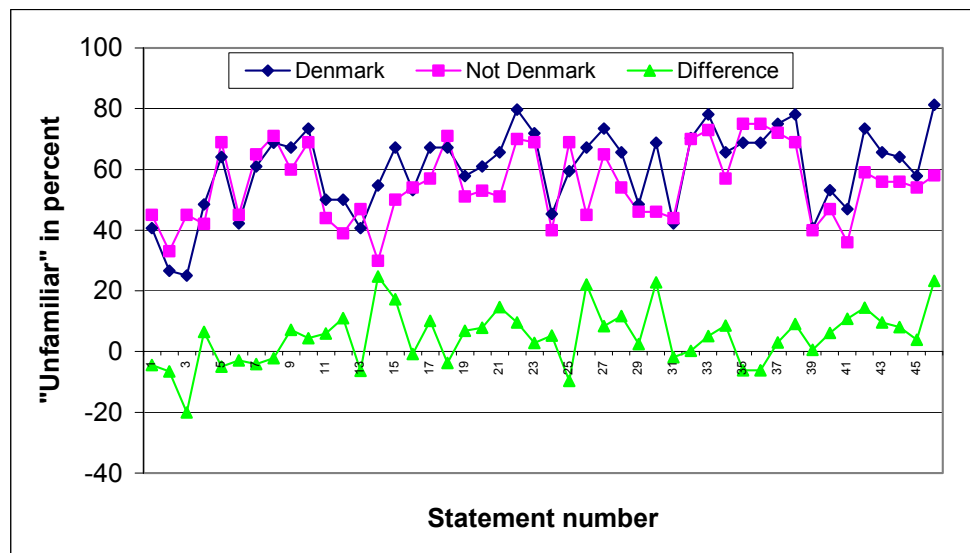


Figure 4.2. Respondents declaring themselves as "unfamiliar". Comparison between Danish and foreign respondents in percentage.

As mentioned above, half of the respondents come from academia (universities and other research institutes) and one third from industry. A cross check has been made on selected statements regarding differences in point of view. From this no significant difference is indicated.

Although respondents complain that the questionnaire is too long and time consuming, it does not strongly affect the response rate. Figure 4.3 demonstrates that the response rate is relatively stable throughout the questionnaire.

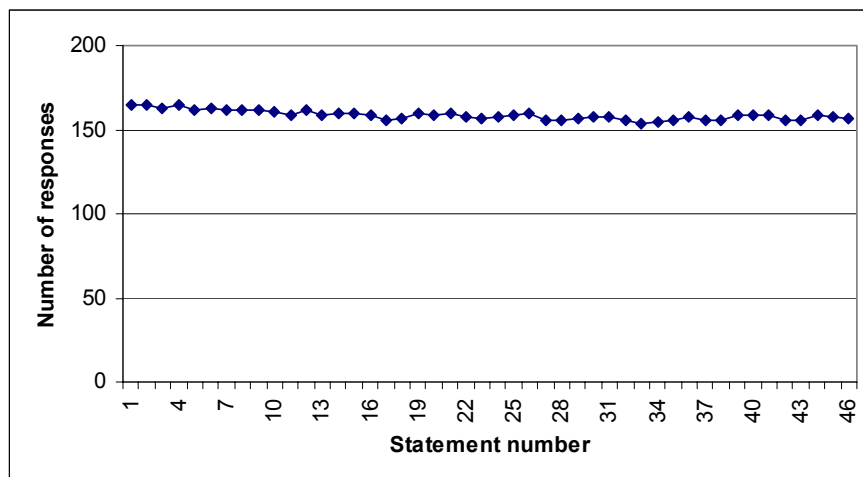


Figure 4.3: Slightly falling response rate

The survey has in general been received positively, and respondents look forward to see the results and conclusions on the STC website.

General remarks from respondents emphasise that the questionnaire is too long to complete and that some of the statements are not clearly formulated and defined and thereby difficult to answer properly. One complains that the statements do not reflect the efforts done within the telecommunication industry on deep dry ICP etch systems. Some respondents point to the time launch of the survey interfering with the holidays in Northern Europe.

Technical problems have likewise been pointed out, including opening the web-based questionnaire as well as the attached word-questionnaire. With some additional help from STC this has in general been solved.

Level of expertise among respondents is sometimes used as an excuse not to complete the questionnaire. This also includes respondents with knowledge about selected sensor types, but without market knowledge, and respondents in the field of application of sensors, but without opinions on the future development.

4.3 The ranking of topics

The numerical results from the survey is presented in Appendix E. Only expert and knowledgeable responses have been included in the variables for each topic, except the responses to “Level of expertise”.

The ranking of the 46 topics on the future development of sensors is based on the combined index of technological feasibility and potential market volume.

Based on the expert and knowledgeable responses to each topic, calculations have been made and weighted for the degrees of technological feasibility and potential market volume (calculation based on total numbers of respondents and weighted values of 100 (High), 0 (Medium), and -100 (Low) respectively, for the degrees of feasibility and impact). The total list of ranked topics is presented in Appendix F.

The combined index of technology feasibility and potential market volume is illustrated in Figure 4.4.

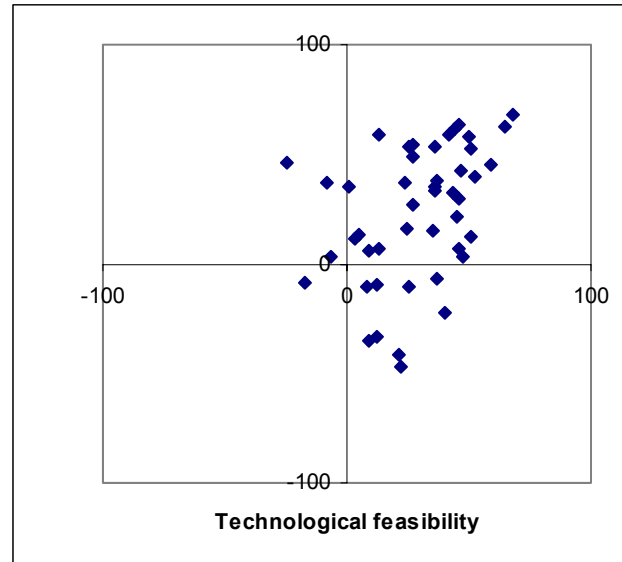


Figure 4.4. Combined index of technological feasibility and market volume

While the top topics are located in Quadrant I (upper right), attention should also be given to topics in Quadrant II (upper left), as these represent high expectations to market volume, but with large unsolved technological challenges. Topics in Quadrant IV (lower right) are also interesting as they represent a technology push looking for potential markets. Quadrant III (lower left) is not interesting having low expectations to both technological feasibility and market volume of the topic.

The top ten topics selected by the combined index of technological feasibility and potential market volume are presented below. Table 4.1 outlines technology, market and combined index together with development stage and time occurrence. Hereafter Table 4.2 focuses on the distribution of specific markets. The barriers for realising the top ten topics are shown in Table 4.3. Table 4.4 and Table 4.5 focus on the middle rankings of statements, while eventually the bottom list is shown in Table 4.6.

Table 4.1 lists the top ten topics, which are selected according to the combined index of technological feasibility and potential market volume. For the three top topics there is a balance between technology feasibility and potential market volume. This is not the case for the remaining topics. Interesting is the technology index within optics (No. 2) and sensors for energy conversion (No. 45) compared to the lower market index. Conversely, the market index is higher than the technology index for DNA-sensors and cheap MEMS for food and health care (No. 36 and 12) as well as biosensors in general (No. 31).

The top-ten list comprises topics covering all types of sensors, except electrical and nuclear sensors. MEMS is rated high together with sensors that are small, low-cost, and flexible. Sensors are also expected to be integrated systems with multiple applications. Among the top topics is the development of DNA-sensors for specific measurement. Among other topics is the widespread use of biosensors, including their application for measuring water quality. Widespread use of sensors is also expected in mobile communication systems, and energy conversion systems.

The top ten list contains topics with advanced development stages, except for one topic on the development of DNA-sensors. The time of occurrence for the majority of the topics is expected to be within the next ten years. The assessment of time of occurrence for the biosensors seems to be more extended with a time period between 2001-2015, except for biosensors measuring water quality.

Table 4.1. Characteristics of top ten topics

Rank	No.	Statement	T in- dex	M in- dex	T+M in- dex	Dev. state	Period of occur- rence
1	14	Practical use of MEMS for miniaturised and low-cost sensor and actuator systems	68	68	68	P	2001-2010 (55-32)
2	40	Widespread use of sensor communication systems based on "fourth generation" mobile communication systems, Internet (WAP)	65	63	64	W	2001-2010 (44-36)
3	36	Development of DNA-sensors measuring genetic diseases and/or genetically modified food	46	64	55	D	2001-2015 (30-41-22)
4	7	Practical use of high frequency (>50G Hz) microwave systems for motion control and collision avoidance	50	58	54	P	2001-2010 (39-39)
5	12	Widespread use of silicon MEMS sensors in applications with unit price <5 EUR in food and health care	44	62	53	W	2001-2010 (31-56)
6	45	Widespread use of sensors in new energy conversion systems (e.g. fuel cells, wind turbines)	59	45	52	W	2001-2015 (30-42-21)
7	24	Widespread use of sensors for measurement of water quality (e.g. micro biological parameters) for application in water recovery, production, monitoring to ensure water supply at global level	51	52	51	W	2001-2010 (44-45)
8	29	Widespread use of lab-on-a-chip sensing in food safety and medical diagnostics (e.g. capillary separation and optical detection)	42	59	50	W	2001-2015 (23-48-25)
9	2	Practical use of integrated optics as key elements in sensors	52	40	46	P	2001-2010 (63-30)
10	31	Widespread use of biosensors	36	54	45	W	2001-2015 (30-36-30)

In the parenthesis the percentages are given for the time periods included. These are 2001-2005; 2006-2010; 2011-2015, and after 2015.

As illustrated in Table 4.2, the markets most influenced by the top ten topics change from topic to topic. The two top topics have an impact on a wide range of markets (No. 14 and 40). For the topics on biosensors, the impact is outspoken on the food and health markets (No. 29, 31, 36). The markets for transport, energy and environment are influenced by the topic on sensors for energy conversion (No. 45). The topic on motion control is mainly oriented towards the markets of transport and security (No. 7), while the sensor for measuring water quality has impact on the markets for agriculture, food and environment (No. 24).

Table 4.2. Top ten and market impact, in percentage

No	Statement	Agriculture	Food processing	Construction	IT/communication	Transport	Energy	Environment	Health care	Domestic appl.	Metal/plastic	Wood/textile	Chemical eng.	Security/defence
14	Practical use of MEMS for miniaturised and low-cost sensor and actuator systems	6	6	3	10	11	7	11	12	10	3	2	9	10
40	Widespread use of sensor communication systems based on "fourth generation" mobile communication systems, Internet (WAP)	8	6	6	14	10	6	10	10	9	5	4	5	8
36	Development of DNA-sensors measuring genetic diseases and/or genetically modified food	17	25	0	0	0	0	14	32	2	0	1	4	5
7	Practical use of high frequency (>50G Hz) microwave systems for motion control and collision avoidance	3	5	4	3	38	4	3	2	9	6	3	3	17
12	Widespread use of silicon MEMS sensors in applications with unit price <5 EUR in food and health care	8	25	2	3	3	2	8	27	8	1	2	7	4
45	Widespread use of sensors in new energy conversion systems (e.g. fuel cells, wind turbines)	2	1	3	5	19	37	16	1	8	2	0	3	5
24	Widespread use of sensors for measurement of water quality (e.g. micro biological parameters) for application in water recovery, production, monitoring to ensure water supply at global level	17	16	1	0	1	3	26	10	7	2	3	12	3
29	Widespread use of lab-on-a-chip sensing in food safety and medical diagnostics (e.g. capillary separation and optical detection)	11	21	0	0	1	0	14	25	5	1	1	13	7
2	Practical use of integrated optics as key elements in sensors	5	8	3	15	7	6	11	14	7	3	2	10	10
31	Widespread use of biosensors	14	21	0	1	0	2	19	22	5	0	1	9	6

Table 4.3 shows which barriers constrain the realisation of the topics. All the topics, but No. 7 put strong emphasis on the limited cross-disciplinary collaboration. The lack of qualified human resources is also highlighted in the majority of the topics (No. 14, 36, 7, 45, 29, 2, 31). For the topics on sensor communication and motion control the lack of standardisation is likewise highlighted. Limited cross-sectorial collaboration is especially emphasised in topics on MEMS and measurement of water quality (No. 12 and 24).

Table 4.3. Top ten topics and barriers for their realisation, in percentage

No.	Statement	A	B	C	D	E	F	G	H	I	J
14	Practical use of MEMS for miniaturised and low-cost sensor and actuator systems	24	15	22	4	3	13	6	1	4	8
40	Widespread use of sensor communication systems based on "fourth generation" mobile communication systems, Internet (WAP)	16	15	19	3	4	21	1	2	9	10
36	Development of DNA-sensors measuring genetic diseases and/or genetically modified food	19	12	22	9	7	6	3	1	16	4
7	Practical use of high frequency (>50G Hz) microwave systems for motion control and collision avoidance	16	14	9	10	9	15	6	1	12	9
12	Widespread use of silicon MEMS sensors in applications with unit price <5 EUR in food and health care	13	18	24	6	9	9	5	4	7	6
45	Widespread use of sensors in new energy conversion systems (e.g. fuel cells, wind turbines)	25	17	19	7	2	7	4	0	2	16
24	Widespread use of sensors for measurement of water quality (e.g. micro biological parameters) for application in water recovery, production, monitoring to ensure water supply at global level	15	21	20	11	9	9	5	0	2	9
29	Widespread use of lab-on-a-chip sensing in food safety and medical diagnostics (e.g. capillary separation and optical detection)	21	14	27	5	6	10	4	0	6	7
2	Practical use of integrated optics as key elements in sensors	22	20	29	2	0	11	4	0	4	7
31	Widespread use of biosensors	22	13	29	5	5	9	5	1	5	7

A = Lack of qualified human resources; B=limited cross-sectorial collaboration;
C = limited cross-disciplinary collaboration; D=lack of regulatory measures;
E = regulatory measures; F=lack of standardisation; G=standardisation;
H = adverse effect on environment and safety; I=lack of public acceptance;
J = other.

The higher middle list comprises topics following the top ten topics and with an index higher than or equal to thirty. From Table 4.4 it appears that the market impact for ultra-small biosensors and the use of polymers and self-contained energy sensors is much larger than the technological feasibility (No. 34, 15, 1, and 43). Conversely, the technological feasibility is larger than the market impact for topics on fibre optical sensors, radio frequency sensing and the use of chemometrics (No. 3, 9, and 17). A more balanced index is shown for topics on optical sensors, use of micro-fluidics, and automotive sensors (No. 6, 20, 13, and 19).

Table 4.4. Higher middle list

Rank	No.	Statement	T index	M Index	T+M index
11	6	Widespread use of optical sensor systems for non-invasive diagnostics	47	43	45
12	34	Development of ultra-small biosensors and actuators with cordless transfer of information for diagnostics and in-vivo control of implanted components in medical or other applications, e.g. implanted glucose-sensor with insulin dosage	27	54	41
13	15	Polymers will become a base material for MEMS devices	25	53	39
14	1	Practical use of polymers instead of traditional materials (e.g. semiconductors) both for simple components and integrated optical systems	27	49	38
15	41	Practical use of sensors for in-situ calibration or self-calibrating sensors and instruments	44	32	38
16	3	Practical use of fibre optic sensors based on advances in fibre optical technologies	46	29	38
17	13	Practical use of micro-fluidics (liquids and gases) in sensors	37	38	37
18	43	Development of flexible, miniaturised energy supply for integration in self-contained sensors	13	59	36
19	30	Widespread use of automotive sensors, e.g. NOx sensors, in industrial applications (e.g. GDI, common rail, domestic appliances, agriculture)	36	36	36
20	4	Widespread use of low-cost optical gas sensors for in-situ detection of gas compositions	36	34	35
21	9	Radio frequency sensing will become important for industrial sensing	45	22	33
22	25	Practical use of chemometrics to combine sensory inputs	51	12	32
23	27	Practical use of enzyme catalysed electrochemical sensors for medical and food safety	24	37	30

The lower middle list comprises topics with a combined index lower than thirty and higher than zero as illustrated in Table 4.5. This list contains some remarkable differences between technological feasibility and the potential market volume. Although the technological feasibility is rated relatively high for low-cost electrical sensors, novel concepts in magnetic sensors, opto-acoustic sensors, use of eddy current and ultrasound sensors, the market impact is very limited (No. 19, 21, 11, 42, 23, and 16). However, market impact is relatively high for topics on sensor systems optics, human perception sensors, and implanted biosensors, but with low technological feasibility (No. 39, 44, and 32).

Table 4.5. Lower middle list

Rank	No.	Statement	T Index	M Index	T+M index
24	20	Practical use of novel concepts for strain, temperature and pressure sensing, e.g. based on advanced ceramic materials	27	27	27
25	19	Practical use of low-cost, electrical sensors for robust strain-gauges	46	7	26
26	21	Practical use of novel concepts in magnetic sensors, e.g. Hall-effect, magneto-resistive and inductive	48	3	25
27	11	Practical use of combinations of optical and acoustic sensors in automated production and control	35	15	25
28	26	Widespread use of artificial noses	24	16	20
29	39	In approx. 1/3 of all new sensor systems, optics largely replace electronics	1	35	18
30	42	Development of high-speed image recognition sensors capable of responding in real time to e.g. athletes' motions	37	-7	15
31	44	Practical use of sensors capable of fully reproducible measurements of human perception (e.g. colour, smell, sound, touch)	-8	37	14
32	32	Sense monitoring via implanted biosensors, e.g. early cancer warning (elucidation stage)	-25	46	10
33	28	Widespread use of functional (interactive) polymers for various applications, e.g. gas sensing, food safety	13	7	10
34	10	Radio frequency will become important for biological and medical diagnostics	5	14	9
35	23	Practical use of eddy current in on-line industrial process control (e.g. identifying cracks in metallic objects)	40	-23	9
36	18	Acoustics will provide for the dominating imaging modality in medicine	9	6	7
37	35	Practical use of specific sensors using living organisms (e.g. genetically modified bacteria) as sensing element	3	12	7
38	16	Widespread use of ultrasound for on-line sensing in production systems	25	-11	7
39	8	Widespread use of microwave sensors to find unwanted objects (metal, paper, rubber etc.) in e.g. food products	12	-10	1

The Bottom-list covers topics that score low on technological feasibility and potential market volume. For details see Table 4.6. As can be seen, especially the potential market volumes are rated low.

Table 4.6. Bottom list

Rank	No.	Statement	T index	M index	T+M Index
40	5	Practical use of non-contact optical sensors for detection of plant conditions (disease and well-ness) in agriculture	8	-10	-1
41	46	Practical use of sensors to substitute human sensation, capable of directly stimulating nerves	-6	3	-2
42	37	Practical use of novel concepts of low-cost X-ray sources utilising ionising radiation for industrial process control	21	-42	-10
43	17	Widespread use of acoustic imaging sensor systems for environmental monitoring and industrial process control	12	-33	-11
44	38	Industrial use of nuclear magnetic resonance sensors	22	-47	-13
45	22	Practical use of superconductors in magnetic sensing	9	-35	-13
46	33	Elucidation of genetic monitoring via implanted sensors to predict a range of parameters, e.g. behaviour, life expectancy	-17	-9	-13

4.4 Technology and market

Technological feasibility

In Figure 4.5 the topics are presented according to the average index of technological feasibility. The technological feasibility is calculated based on total numbers of respondents and weighted values of 100 (High), 0 (Medium), and -100 (Low) respectively, for the degrees of feasibility. The average index does not include topics assessed as having no technological feasibility.

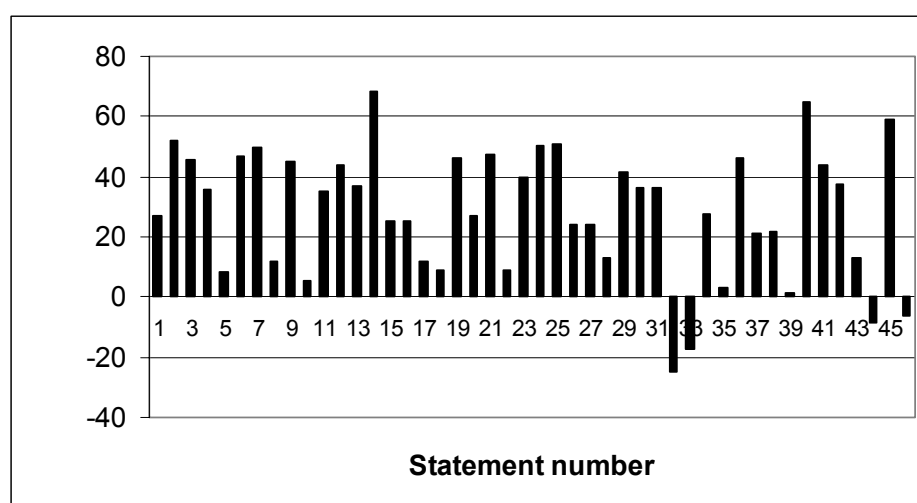


Figure 4.5. Index of technological feasibility

The **top list** of technological feasibility is presented in Table 4.7. Due to similar average index of the last three topics, twelve topics are listed. From the list it may be observed that the topics cover a variety of sensor types and that all but one have an advanced development state. This may indicate that the technological challenges to a large extent are considered to be easily solved or overcome. The high rank of development within DNA-sensors may reflect positive expectation to an emerging research area.

Table 4.7. Top-ten [twelve] of technological feasibility

Rank	No.	Statement	Index
1	14	Practical use of MEMS for miniaturised and low-cost sensor and actuator systems	68
2	40	Widespread use of sensor communication systems based on "fourth generation" mobile communication systems, Internet (WAP)	65
3	45	Widespread use of sensors in new energy conversion systems (e.g. fuel cells, wind turbines)	59
4	2	Practical use of integrated optics as key elements in sensors	52
5	25	Practical use of chemometrics to combine sensory inputs	51
6	24	Widespread use of sensors for measurement of water quality (e.g. micro biological parameters) for application in water recovery, production, monitoring to ensure water supply at global level	51
7	7	Practical use of high frequency (>50G Hz) microwave systems for motion control and collision avoidance	50
8	21	Practical use of novel concepts in magnetic sensors, e.g. Hall-effect, magneto-resistive and inductive	48
9	6	Widespread use of optical sensor systems for non-invasive diagnostics	47
10	19	Practical use of low-cost, electrical sensors for robust strain-gauges	46
11	36	Development of DNA-sensors measuring genetic diseases and/or genetically modified food	46
12	3	Practical use of fibre optic sensors based on advances in fibre optical technologies	46

The **bottom list** of technological feasibility or topics with an average index below zero are constrained to four: two topics regarding the elucidation of implanted systemic sensors to monitor or predict a range of parameters and two topics regarding the practical use of biochemical sensors to measure or substitute human sensation. This may indicate that expectations should not be too optimistic, neither for the elucidation of implanted bio-sensors nor for the use of human-like sensors. However, this partly contradicts the positive expectation to the development of DNA-sensors stated above. For more details, see Table 4.8.

Table 4.8. Bottom list of technological feasibility

Rank	No.	Statement	Index
43	46	Practical use of sensors to substitute human sensation, capable of directly stimulating nerves	-6
44	44	Practical use of sensors capable of fully reproducible measurements of human perception (e.g. colour, smell, sound, touch)	-8
45	33	Elucidation of genetic monitoring via implanted sensors to predict a range of parameters, e.g. behaviour, life expectancy	-17
46	32	Sense monitoring via implanted bio-sensors, e.g. early cancer warning (elucidation stage)	-25

Market volume

The respondents were asked to rate the potential global market volume after the realisation of the statement.

Figure 4.6 shows the index of potential market volume of the 46 topics. The potential market volume is calculated based on total numbers of respondents and weighted values of 100 (High), 0 (Medium), and -100 (Low) respectively, for the degrees of volume. The average index does not include topics assessed as having no market volume.

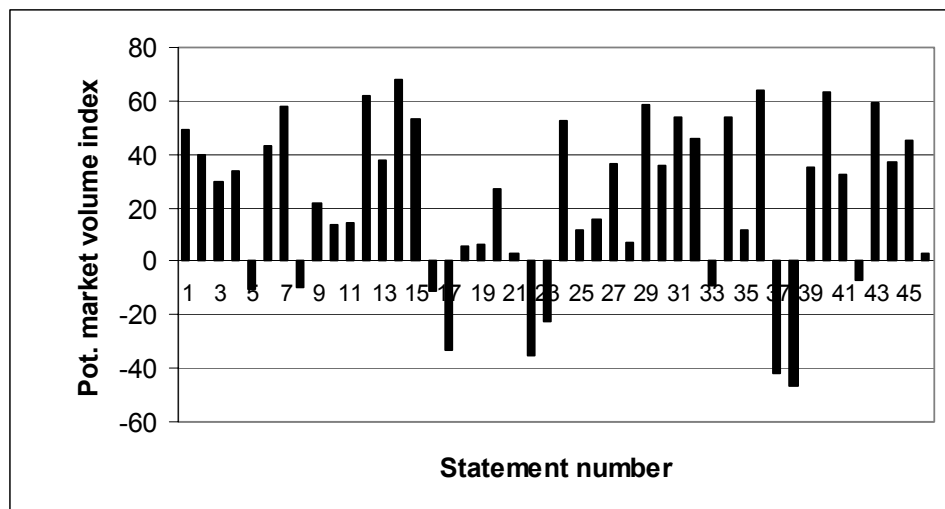


Figure 4.6. Index of potential market volume

Contrarily to the index on technological feasibility, there seem to be more obstacles in realising potential market volume. Table 4.9 shows the **top-ten topics**, which are considered to have the highest average index of potential market volume. Expectations are high regarding the practical and widespread use of miniaturised and low-cost sensors in general, and MEMS in particular. Interesting is also the high rank of the development of DNA-sensors and widespread use of biosensors. This may indicate a certain market pull/demand for this type of sensors. Topics regarding self-contained sensors and lab-on-a-chip sensing are likewise expected to have a high market impact, as have microwave sensors for the transport industry.

Table 4.9. Top-ten of potential market volume

Rank	No.	Statement	Index
1	14	Practical use of MEMS for miniaturised and low-cost sensor and actuator systems, which can operate as hybrids	68
2	36	Development of DNA-sensors measuring genetic diseases and/or genetically modified food	64
3	40	Widespread use of sensor communication systems based on "fourth generation" mobile communication systems, Internet (WAP)	63
4	12	Widespread use of silicon MEMS sensors in applications with unit price <5 EUR in food and health care	62
5	43	Development of flexible, miniaturised energy supply for integration in self-contained sensors	59
6	29	Widespread use of lab-on-a-chip sensing in food safety and medical diagnostics (e.g. capillary separation and optical detection)	59
7	7	Practical use of high frequency (>50G Hz) microwave systems for motion control and collision avoidance	58
8	34	Development of ultra-small biosensors and actuators with cordless transfer of information for diagnosis and in-vivo control of implanted components in medical or other applications, e.g. implanted glucose-sensor with insulin dosage	54
9	31	Widespread use of biosensors	54
10	15	Polymers will become a base material for MEMS devices	53

The **bottom list** of expectations to market volume is presented in Table 4.10. The bottom list first and foremost comprises topics at the stages of practical use or widespread use. This may indicate that market segments are either relatively small/unprofitable or that the topic is not competitive to other technologies. Topics with an early development stage are normally expected to have low market impact.

Table 4.10. Bottom-list of potential market volume

Rank	No.	Statement	Index
37	42	Development of high-speed image recognition sensors capable of responding in real time to, e.g. athletes' motions	-7
38	33	Elucidation of genetic monitoring via implanted sensors to predict a range of parameters, e.g. behaviour, life expectancy	-9
39	8	Widespread use of microwave sensors to find unwanted objects (metal, paper, rubber etc.) in e.g. food products	-10
40	5	Practical use of non-contact optical sensors for detection of plant conditions (disease and wellness) in agriculture	-10
41	16	Widespread use of ultrasound for on-line sensing in production systems	-11
42	23	Practical use of eddy current in on-line industrial process control (e.g. identifying cracks in metallic objects)	-23
43	17	Widespread use of acoustic imaging sensor systems for environmental monitoring and industrial process control	-33
44	22	Practical use of superconductors in magnetic sensing	-35
45	37	Practical use of novel concepts of low-cost X-ray sources utilising ionising radiation for industrial process control	-42
46	38	Industrial use of nuclear magnetic resonance sensors	-47

4.5 Period of occurrence

The topics are expected to be realised mainly before 2011. This is not surprising given the dominance of practical and widespread use in many statements (see also Table 3.6 in the previous chapter). Figure 4.7 shows that 39% of the topics are expected to be realised between 2006-2010, 37% of the topics between 2001-2005 and the remaining topics after 2010, including 4% that will never occur.

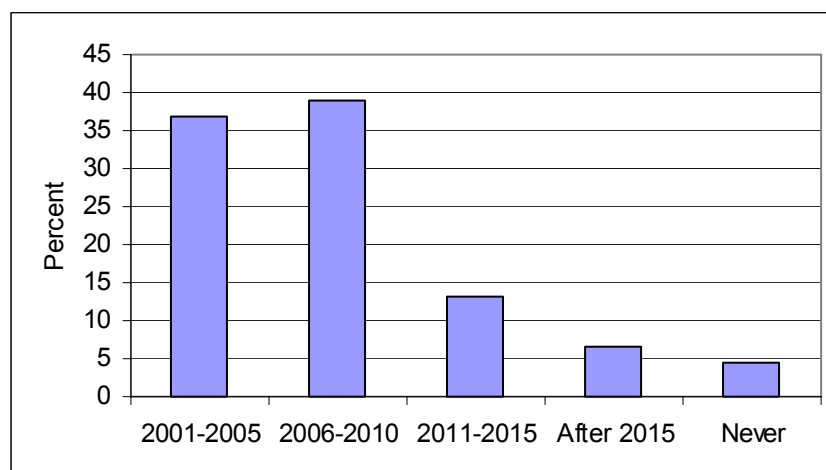


Figure 4.7. Time occurrence for all sensors

The analysis of the responses indicating that the topic will “Never” occur has been conducted on the basis that if the “Never” exceeds 10% of total expertise and knowledgeable responses, it is classified as significant. These topics are shown in Table 4.11. Three of the topics comprise biosensors in various development stages, ranging from elucidation to practical use. Comparing the “Never” responses with the bottom list of technological feasibility (Table 4.8) and potential market volume (Table 4.10) it reveals some conformity for implanted sensors (No. 33). For human perception sensors (No. 44) there is also accordance with the bottom list of technological feasibility.

Table 4.11. “Never” responses

No.	Statement	Never
33	Elucidation of genetic monitoring via implanted sensors to predict a range of parameters, e.g. behaviour, life expectancy	28%
39	In approx. 1/3 of all new sensor systems, optics largely replace electronics	27%
18	Acoustics will provide for the dominating imaging modality in medicine	25%
44	Practical use of sensors capable of fully reproducible measurements of human perception (e.g. colour, smell, sound, touch)	16%
32	Sense monitoring via implanted biosensors, e.g. early cancer warning (elucidation stage)	11%

The time occurrence for each sensor type is shown in Figure 4.8. For both magnetic and electrical sensors more than half of the topics are supposed to be realised before 2005. Also for electromagnetic sensors slightly less than half of the topics are supposed to be realised before 2005. For nuclear, mechanical, chemical, and systemic issues the realisation of the topics is mainly perceived to be during the period of 2006-2010. However, both chemical and systemic issues have topics with a longer realisation horizon from 2011 and onwards. In particular the systemic issues have a number of topics, which are not expected ever to be realised.

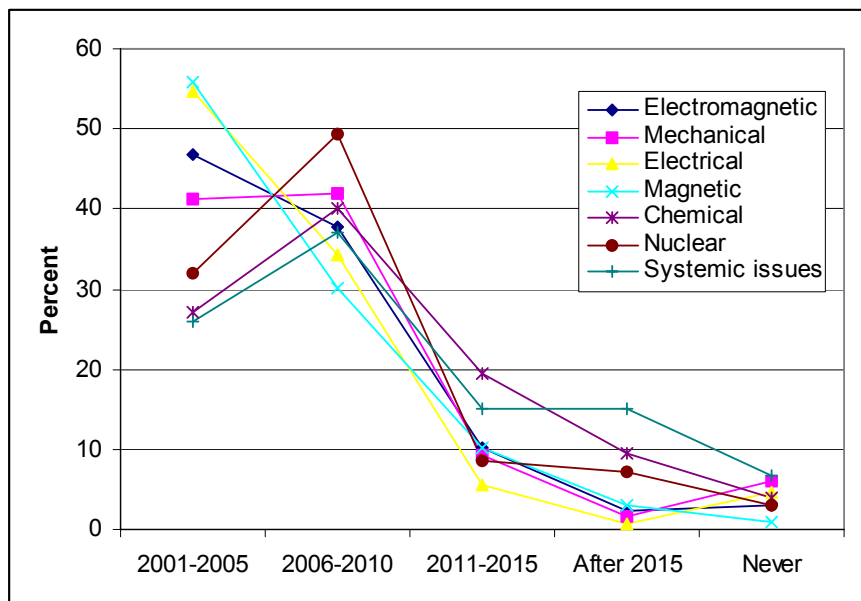


Figure 4.8. Time occurrence by sensor types

4.6 Market sectors most heavily impacted

The market sector most heavily impacted by sensors is the health care sector with 20% of all topics. From Figure 4.9 it also appears that sensors have impact on food processing sector (12%) and the environment sector (11%). Some impact is on markets such as agriculture (8%), chemical engineering (8%), domestic and other appliances (7%), security and defence (7%), transport (6%), and energy (6%). Less impact is made in sectors such as construction/housing (3%), wood and textile (3%), IT/communication (4%), and metal and plastic processing (5%).

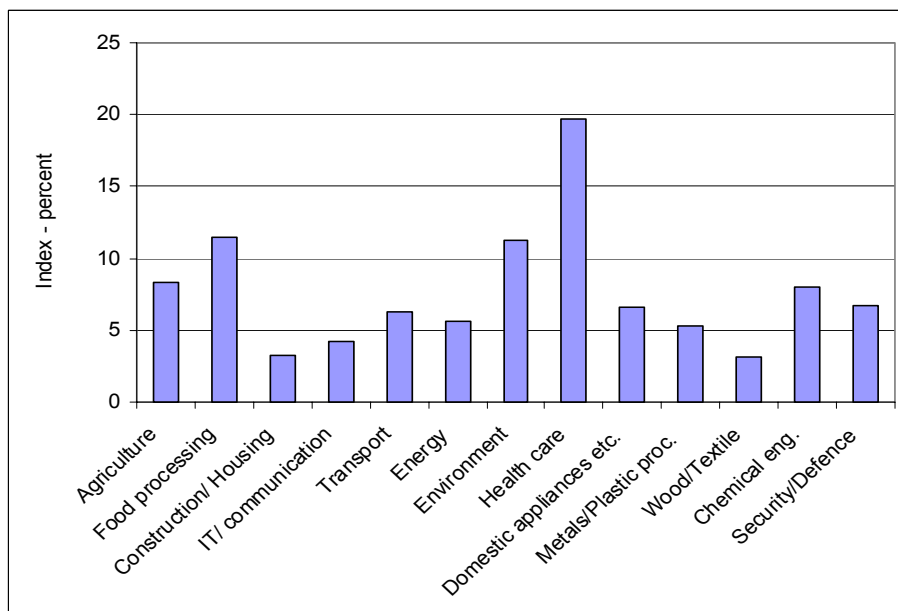


Figure 4.9. Market impact for all sensor types

However, it should be noticed that in some statements suggestions are made as to which market sectors will apply the topic. Reference to the health sector is for example mentioned directly and indirectly in 11 statements (No. 6, 10, 2, 18, 22, 29, 32, 33, 34, 36, 42, and 46).

When looking at which market impact sensor types have, Figure 4.10 shows that sensor types such as chemical, mechanical, systemic, and electromechanical sensors have largest impact on the health sector, while magnetic sensors seem to have most impact on the metal/plastic production. For electrical sensors some market impact is expected on the housing/construction, transport, energy, and metal/plastic processing sectors. Nuclear sensors are expected to have most impact on the food, metal/plastic processing, and wood/textile sectors.

Chemical sensors do also have some impact on the agricultural and food sectors, but almost none on the housing, IT, transport, energy, metal/plastic processing, and wood/textile sectors. Mechanical sensors have also impact on the food, environment and chemical engineering sectors. Sectors such as transport and energy are also influenced by magnetic sensors.

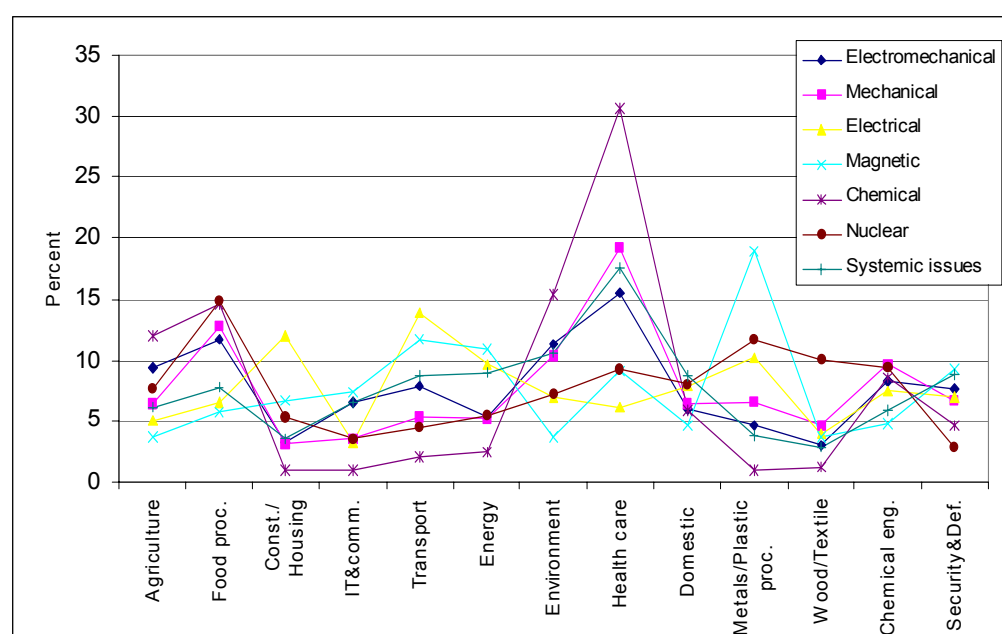


Figure 4.10. Market impact by sensor types

4.7 Constraints/barriers for realising the statement

Realisation of the statement may be constrained by a number of framework conditions that are central to the development of the technology and the markets.

Barriers are first and foremost limited cross-disciplinary collaboration (22%) as it is indicated in Figure 4.11. But lack of qualified human resources (20%) and lack of cross-sectorial collaboration (17%) are also highlighted as important barriers.

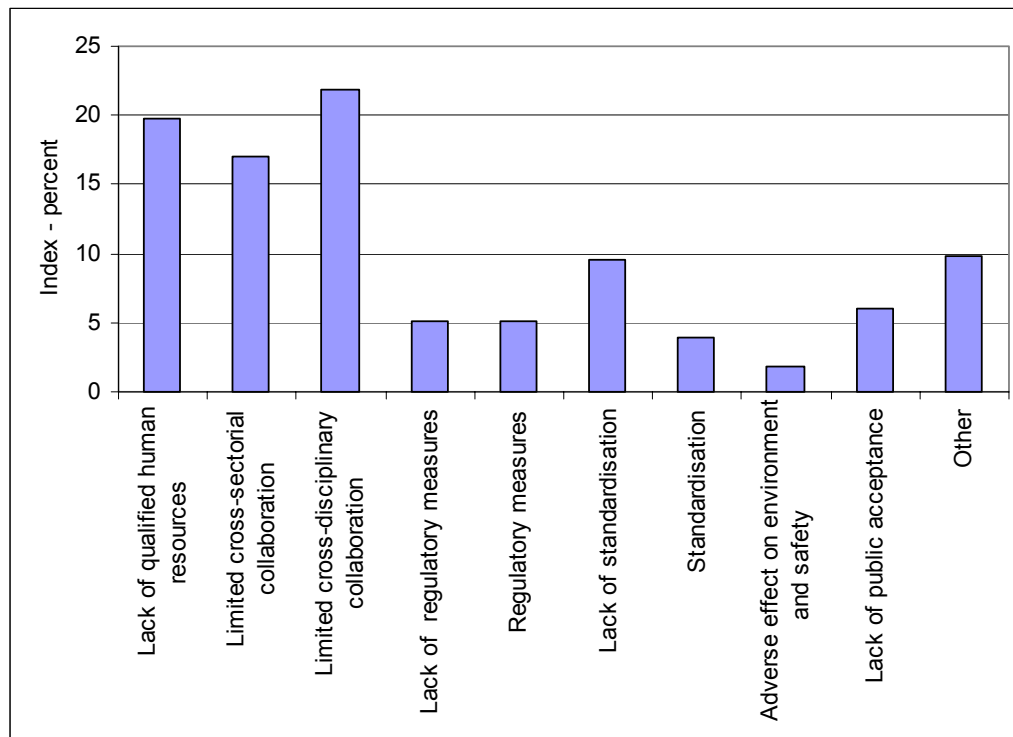


Figure 4.11. Barriers for realising the sensor topics

The lack of standardisation (10%) is mentioned, in particular regarding the topics on widespread use of sensor communications systems (No. 40) and of artificial noses (No. 26). Too much standardisation (4%) is especially related to topics regarding electrical sensors for strain-gauges (No. 19) and optical sensors for gas compositions (No. 4). Some attention is paid to lack of regulation (5%) or regulation (5%). The first concerns for example topics such as automotive sensors (No. 30) and optical gas sensors (No. 4). The latter regards primarily topics on implanted sensors and biosensors (No. 33 and 34).

Lack of public acceptance (6%) is the case for topics such as implanted sensors (No. 33) and X-ray sources for industrial processes (No. 37).

Under the headline of “Other”, attention is drawn to financial constraints, both public research funding and private investments (No. 2, 4, 6, 14, 20, 21, 24, 26, 27, 29, 31, 44, 46). For three specific topics on the use of implanted sensors, constraints comprise legal implications (No. 32, 33, and 34).

Figure 4.12 shows which barriers matter for each sensor type. For all sensor types the three most important barriers for realising the topic are: lack of quali-

fied human resources, along with, limited cross-sectorial and cross-disciplinary collaboration. The largest barrier for realising topics in which electromagnetic, mechanical, and chemical sensors are included is assumed to be limited cross-disciplinary collaboration. For magnetic, nuclear and systemic sensor topics the largest barrier is lack of qualified human resources, whereas for electrical sensors it is the cross-sectorial collaboration, e.g. between academia and industry. For nuclear sensors it should also be mentioned that the lack of public acceptance is perceived as an important barrier.

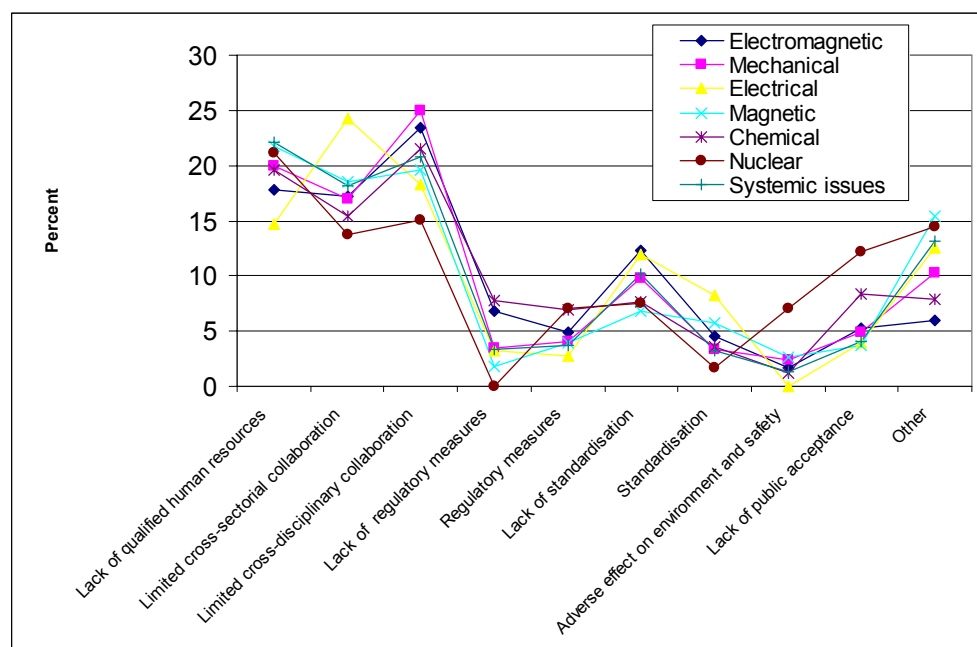


Figure 4.12. Barriers for realising the topic by sensor type

4.8 Summary of survey results

The sensor technology foresight is basically designed as an adapted Delphi investigation. It is designed by two rounds of expert workshops and dialogue about future trends and issues and followed by a larger anonymous survey among experts in order to validate the statements on the future development of sensor technologies.

The survey was launched both with a web-based questionnaire and a word-based questionnaire and forwarded by email to approximately 1,200 identified sensor experts. The total number of respondents were 174, with 143 submitted directly via the Internet. This makes a response rate of 16%. Respondents come primarily from the areas of research and development (75%), and half of the respondents come from universities and other research institutes. More than one-third though come from the industry. There are in particular many expert respondents within MEMS sensors, fibre optical sensors, and biosensors. The survey has in general been received positively, though there is also some criticism that the questionnaire is too long and complicated and also haunted by some minor technical problems.

The ranking of topics is based on the combined index of technological feasibility and potential market volume among expert or knowledgeable respondents.

The top-ten list comprises topics covering all types of sensors, except electrical and nuclear sensors. MEMS is rated high together with sensors that are small, low-cost, and flexible. Sensors are also expected to be integrated systems with multiple applications. The list contains topics with advanced development stages, except for one topic on the development of DNA-sensors. The time of occurrence for the majority of the topics is expected to be within the next ten years. The markets most influenced by the top ten topics change from topic to topic. The two top topics have an impact on a wide range of markets (No. 14 and 40). For the topics on biosensors, the impact is outspoken on the food and health markets (No. 29, 31, 36). These markets are also impacted by a different type – MEMS sensors. The markets for transport, energy, and environment are influenced by the topic on sensors for energy conversion (No. 45). The topic on motion control is mainly oriented towards the markets of transport and security (No. 7), while the sensor for measuring water quality has impact on the markets for agriculture, food and environment (No. 24). The most important barriers for realising all ten topics, but No. 7 are limited cross-disciplinary collaboration. The lack of qualified human resources is also highlighted in the majority of the topics (No. 14, 36, 7, 45, 29, 2, 31). For the topics on sensor communication and motion control the lack of standardisation is likewise highlighted (No. 40 and 7). Limited cross-sectorial collaborations is especially emphasised in topics on MEMS and measurement of water quality (No. 12 and 24).

The higher middle list of topics shows that the market impact for ultra-small biosensors and the use of polymers and self-contained energy sensors is much larger than the technological feasibility (No. 34, 15, 1, and 43). On contrarily, the technological feasibility is larger than the market impact for topics on fibre optical sensors, radio frequency sensing and the use of chemometrics (No. 3, 9, and 17). A more balanced index is shown for topics on optical sensors, use of micro-fluidics, and automotive sensors.

The lower middle list contains some remarkable differences between technological feasibility and the potential market volume. Although the technological feasibility is rated relatively high for low-cost electrical sensors, novel concepts in magnetic sensors, optic-acoustic sensors, use of eddy current and ultrasound sensors, the market impact is very limited (No. 19, 21, 11, 42, 23, and 16). However, market impact is relatively high for topics on sensor systems optics, human perception sensors, and implanted biosensors, but with low technological feasibility (No. 39, 44, and 32).

Conflicting judgement seems to be on biosensors. On the one hand widespread use of biosensors and development of DNA sensors are included in the top ten list; on the other hand the inclusion of elucidation of implanted bio-sensors and the use of human-like sensors in the bottom list of technological feasibility partly contradicts the positive judgement stated above.

Time of occurrence is for most topics expected to be realised mainly before 2011. This is not surprising given the dominance of “practical” and “widespread use” in many statements. 39% of the topics are expected to be realised between 2006-2010, 37% of the topics between 2001-2005 and the remaining topics after 2010, including 4% that will never occur. The analysis of the responses indicating that the topic will “Never” occur (more than 10% of total expertise and knowledgeable responses) shows that three of the topics comprise biosensors in various development stages, ranging from elucidation to practical use. Comparing the “Never” responses with the bottom list of technological feasibility and

potential market volume it reveals some conformity for implanted sensors and human perception sensors.

Market sector most heavily impacted by sensors is the health care sector with 20% of all topics. It also appears that sensors have impact on the food processing sector (12%) and the environment sector (11%). Some impact is on sectors such as agriculture (8%), chemical engineering (8%), domestic and other appliances (7%), security and defence (7%), transport (6%), and energy (6%). Less impact is made in sectors such as construction/housing (3%), wood/textile (3%), IT/communication (4%), and metal and plastic processing (5%).

Barriers for realising the topics cover a number of framework conditions that are central to the development of the technology and the markets. These are first and foremost limited cross-disciplinary collaboration (22%). But lack of qualified human resources (20%) and lack of cross-sectorial collaboration (17%) are also highlighted as important barriers. The lack of standardisation (10%) is mentioned, in particular regarding the topics on widespread use of sensor communications systems (No. 40) and of artificial noses (No. 26). Too much standardisation (4%) is especially related to topics regarding electrical sensors for strain-gauges (No. 19) and optical sensors for gas compositions (No. 4). Some attention is paid to lack of regulation (5%) or regulation (5%). The first concerns for example topics such as automotive sensors (No. 30) and optical gas sensors (No. 4). The latter regards primarily topics on implanted sensors and biosensors (No. 33 and 34). Lack of public acceptance (6%) is the case for topics such as implanted sensors (No. 33) and X-ray sources for industrial processes (No. 37).

5 Conclusion

Sensor technology is a rapidly growing area of research with many products already on the market, which promise to continue to have a critical role in technologies of the future. Sensors span all sectors of industry and often offer products the innovative edge that lead to their competitive advantage. Knowledge about sensors, their applications and their future developments thereby helps to position organisations to grasp emergent opportunities.

Therefore, the Sensor Technology Center A/S (STC) in co-operation with Risø National Laboratory has carried out a sensor technology foresight in order to strengthen a strategic outlook on sensor technology, more specifically:

1. To present some scenarios of the future developments in sensor technology with respect to technology, application and market issues in a time-frame of 2000 to 2015.
2. To contribute as decision support in prioritising research, development and commercialisation of sensor technology.
3. To maintain and develop STC's networks within sensor technology.
4. To test elements of a Technology Foresight methodology in a quite narrow area of technology.

The foresight project has been performed in the period October 2000 – September 2001.

The project consisted of 6 activities divided into two main phases: The first phase concerned the strategic technology scanning. Technology foresight depends on technology insight. One way of embarking on a technology foresight is to define the system under examination and to structure the technology foresight process. Strategic technology scanning is concerned with “looking ahead”. It is essentially an exploration of the future technological landscape, aiming at discerning its major features and significant patterns of change.

The second phase built on the production of a gross list of statements about the future development of sensors and comprised a larger survey to validate expert judgements on a net list of 46 sensor topics. The sensor technology foresight is basically designed as an adapted Delphi investigation. It is designed by two rounds of expert workshops and dialogue about future trends and issues and followed by a larger anonymous survey among experts in order to validate the statements on the future development of sensor technologies.

Sensors and sensor systems perform a diversity of sensing functions allowing the acquisition, capture, communication, processing and distribution of information about the states of physical systems. This may be chemical composition, texture and morphology, large-scale structure, positions and also dynamics. It is a characteristic feature of a sensor that the device is tailored to the environment in which it is to operate.

The conclusions of the sensor technology report are thus based on:

- 1) a scanning of existing forward looking literature on sensor technology
- 2) a number of workshops with Danish and international participants, and
- 3) an international Delphi questionnaire survey with 174 respondents. Half of the Delphi-respondents came from universities and other research institutes, and approximately one-third came from industry.

The study has analysed six **types of sensors** (covering 13 sub-types) and, in addition, a number of systemic issues. All three sources of information indicate the same pattern regarding future attractiveness of sensor types. MEMS- and optical sensors, biochemical/biological sensors together with systemic issues are all expected to be the most interesting sensor types over the next 10 years regarding market volume. Expectations of present and future market importance of a number of sensor types are indicated in the figure below.

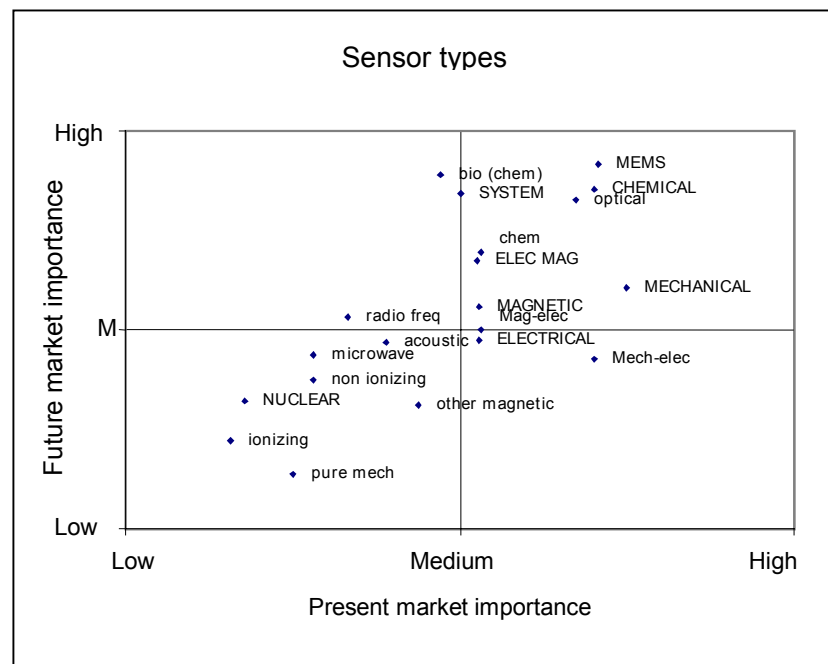


Figure 5.1. Estimation of present and future market importance for sensors

The study indicates some **technological challenges**. The expected market impact for ultra-small biosensors and the use of polymers and miniaturised energy supply for integration in self-contained sensors is much larger than the technological feasibility.

Areas in which the technological feasibility is larger than the potential market volume include fibre optical sensors, radio frequency sensing, eddy current and ultrasound for on-line sensing in production systems, nuclear based sensors and the use of chemometrics.

General **technological key features** are expected to be quite generic: Low price, small size, robustness, dispensability, and the ability to be self-calibrating. Future sensors are expected to be integrated systems with multiple applications.

Highlights from the survey are:

- **The submission of the questionnaire and the responses.** Both a web-based questionnaire and a word-based questionnaire were forwarded by

email to approximately 1,200 identified sensor experts. The total number of respondents were 174, with 143 submitted directly via the Internet. This makes a response rate of 16%. Respondents come primarily from the areas of research and development (75%), and half of the respondents come from universities and other research institutes. More than one-third though come from industry. In particular, there are many expert respondents within MEMS sensors, fibre optical sensors, and biosensors. The survey has in general been received positively, though there is also some criticism that the questionnaire is too long and complicated and also haunted by some minor technical problems.

- **The top ten list** appears from the table below. The ranking of topics is based on the combined index of technological feasibility and potential market volume among expert or knowledgeable respondents.

Rank	No.	Statement	Index
1	14	Practical use of MEMS for miniaturised and low-cost sensor and actuator systems	68
2	40	Widespread use of sensor communication systems based on "fourth generation" mobile communication systems, Internet (WAP)	64
3	36	Development of DNA-sensors measuring genetic diseases and/or genetically modified food	55
4	7	Practical use of high frequency (>50G Hz) microwave systems for motion control and collision avoidance	54
5	12	Widespread use of silicon MEMS sensors in applications with unit price <5 Euro in food and health care	53
6	45	Widespread use of sensors in new energy conversion systems (e.g. fuel cells, wind turbines)	52
7	24	Widespread use of sensors for measurement of water quality (e.g. micro biological parameters) for application in water recovery, production, monitoring to ensure water supply at global level	51
8	29	Widespread use of lab-on-a-chip sensing in food safety and medical diagnostics (e.g. capillary separation and optical detection)	50
9	2	Practical use of integrated optics as key elements in sensors	46
10	31	Widespread use of biosensors	45

- **Characteristics of the top ten.** The top-ten list covers all types of sensors, except electrical and nuclear sensors. MEMS is rated high together with sensors that are small, low-cost, and flexible. Sensors are also expected to be integrated systems with multiple applications. The list contains topics with advanced development stages, except for one topic on DNA-sensors. The time of occurrence for the majority of the topics is expected to be within the next ten years. The markets most influenced by the top ten topics change from topic to topic. Two topics have an impact on a wide range of markets (MEMS and sensor communication system). Topics on biosensors have impact on the food and health markets, whereas sensors for energy conversion have impact on the markets for transport, energy, and environment. The topic on motion control is mainly oriented towards the markets of transport and security, while the sensor for measuring water quality has impact on the markets for agriculture, food, and environment. The most important barriers for realising all ten topics, but one are limited cross-disciplinary collaboration. The lack of qualified human resources is also highlighted in the majority of the topics.

- **The higher middle list** of topics shows that the expected market impact for ultra-small biosensors and the use of polymers and self-contained energy sensors is much larger than the technological feasibility. Conversely, the technological feasibility is larger than the market impact for topics on fibre optical sensors, radio frequency sensing and the use of chemometrics.
- **Conflicting judgement** seems to be on biosensors. On the one hand widespread use of biosensors is included in the top ten list; on the other hand the inclusion of implanted bio-sensors and human-like sensors in the bottom list of technological feasibility partly contradicts the positive judgement stated above.
- **Time of occurrence** is expected to be realised mainly before 2011. This is not surprising given the dominance of “practical” and “widespread use” in many statements. 39% of the topics are expected to be realised between 2006-2010, 37% of the topics between 2001-2005 and the remaining topics after 2010, including 4% that will never occur. The latter includes a.o. topics on biosensors in various development stages.
- **Market sector most heavily impacted by sensors** is the health care sector with 20% of all topics. It also appears that sensors have impact on the food processing (12%), and environment sector (11%). Some impact is made on sectors such as agriculture (8%), chemical engineering (8%), domestic and other appliances (7%), security and defence (7%), transport (6%), and energy (6%). Less impact is made in sectors such as construction/housing (3%), wood/textile (3%), IT/communication (4%), and metal and plastic processing (5%).
- **Barriers for realising the topics** cover a number of framework conditions that are central to the development of the technology and the markets. These are first and foremost limited cross-disciplinary collaboration (22%). But lack of qualified human resources (20%) and lack of cross-sectorial collaboration (17%) are also highlighted as important barriers. The lack of standardisation (10%) is mentioned, in particular regarding the topics on sensor communications systems and artificial noses. Lack of public acceptance (6%) is the case for topics such as implanted sensors and X-ray sources for industrial processes.

6 Literature

Erhvervsfremme Styrelsen (2000). *Erhvervsudsigten. Trends der vil påvirke dansk erhvervsliv de kommende 10 år*, Statens information.

Hollingum, J. (1999). *Foresight launches three sensor programmes*, Sensor Review, 19(2), 116-120.

Institute for the Future (1997). *Sensors: The next wave of infortech innovation*, 1997 Ten-year forecast, 115-122.

Kretschmer, T., Kohlhoff, J. (1997). *Sensorik: Überblick und Trends*, Fraunhofer Institut Naturwissenschaftlich-Technische Trendanalysen.

Loveridge, D., Georghiou, L., Nedeva, M. (1995). *United Kingdom Technology Foresight Programme. Delphi Survey*. PREST. The University of Manchester. (1995). 543 pp.

Magnusson, L., Zenker, S., Rossander, O., Kullinger, B. (2000). *Swedish Technology Foresight. The Foresighted Society*, A synthesis report from the Swedish technology foresight project, 57 pp.

McGhee, J., Henderson, I.A., Sydenham, P.H. (1999). *Sensor science - essentials for instrumentation and measurement technology*, Measurement, **25**, 89-113.

Moore, G.F., Arkinson, H., Lane, R., Eng, W.S.F. (1997). *Sensing the Future. Sensors in Manufacturing and Materials*, A Report by the Foresight Sensors Action Group, Department of Trade and Industry, 22 pp.

NISTEP (1997). *The sixth technology forecast survey - Future Technology in Japan Toward the Year 2025*. National Institute of Science and Technology Policy & Science and Technology Agency (Japan). NISTEP report no. 52. (1997). 543 pp.

Pendril, L. (2000). *Forskningsnätverk för tillämpad sensorutveckling och mätteknik*, Sveriges Provnings- och Forskningsinstitut, SP RAPPORT 2000:12

Porter, M.E. (1990). *The Competitive Advantage of Nations*, The Free Press, 855 pp.

RAND Europe (1998). *Technology radar. Global views on strategic technologies*, Dutch Ministry of Economic Affairs, 50 pp.

RAND Europe (1998). *Technology radar. Main report and executive summary*, Dutch Ministry of Economic Affairs, 115 pp.

STC (1999). Presentation from Sensor Technology Center,
<http://www.sensortec.dk/>

Teknologisk Institut (2000). *Industrielle behov for nye sensorer til fysiske målinger - analyse på baggrund af telefoninterview af 23 virksomheder*.

Wyk, R.J. van (1997). *Strategic Technology Scanning*, Technological Forecasting and Social Change, **55**, 21-38.

Title and authors

Sensor Technology Foresight

Per Dannemand Andersen, Birte Holst Jørgensen & Birgitte Rasmussen

ISBN	ISSN
87-550-2938-8	0106-2840
Department or group	Date
Systems Analysis Department	November 2001
Groups own reg. number(s)	Project/contract No(s)
SYS-2000-311-23	

Sponsorship

Sensor Technology Center A/S together with Risø National Laboratory

Pages	Tables	Illustrations	References
57 (plus appendices)	16	23	16

Abstract (max. 2000 characters)

The Sensor Technology Center A/S (STC) in co-operation with Risø National Laboratory has carried out a sensor technology foresight in order to strengthen a strategic outlook on sensor technology. The technology foresight (with a timeframe of 2000 to 2015) has been performed in the period October 2000 – September 2001.

The conclusions of the sensor technology report are based on 1) a scanning of existing forward looking literature on sensor technology, 2) a number of workshops with Danish and international participants and 3) an international survey with 174 respondents. Half of the respondents came from universities and other research institutes, and approximately one-third came from industry.

The study has analysed **six types of sensors** (covering 13 sub-types) and, in addition, a number of systemic issues. All three sources of information indicate the same pattern regarding future attractiveness of sensor types. MEMS- and optical sensors, biochemical/biological sensors together with systemic issues are all expected to be the most interesting sensor types over the next 10 years regarding market volume. General **technological key features** are expected to be quite generic: low price, small size, robustness, dispensability, and the ability to be self-calibrating. Future sensors are expected to be integrated systems with multiple applications.

The **market sectors** most influenced by new sensor technology change from topic to topic. But a general conclusion is that health care is the market sector most heavily impacted by new sensor technology. It also appears that new sensor technology will affect food processing and the environment sector. Some impact is made on sectors such as agriculture, chemical engineering, domestic and other appliances, security and defence, transport, and energy. Less impact is made in sectors such as construction/housing, wood/textile, IT/communication, and metal and plastic processing. The survey does not challenge the generally accepted perception that the transport sector also in a 10 year future will be a driving force in developing new sensor technology.

Descriptors INIS/EDB



Risø is a National Laboratory under the Ministry of Information Technology and Research with its own board of governors. Risø conducts research in the natural and technical sciences with the objective to help create prosperity and environmental sustainability through research-based technological development. Our main research areas are sustainable energy production, industrial technology and bioproduction. Our customers come from industry, research centers and Danish authorities. Risø contributes to the Danish education of young researchers through PhD.- and post doc-programmes. Moreover Risø advises government authorities on nuclear matters.

The research is organised in the following programme areas:

- Wind energy
- Systems and technology analyses
- Energy materials
- Polymers
- Optics and sensors
- Plant biotechnology
- Radiation safety

ISBN 87-550-2938-8

ISBN 87-550-2939-6 (Internet)

ISSN 0106-2840

**Copies of this publication
are available from**

**Risø National Laboratory
Information Service Department
P.O. Box 49
DK-4000 Roskilde
Denmark
Telephone +45 4677 4004
risoe@risoe.dk
Fax +45 4677 4013
Website www.risoe.dk**